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THE PRESENT STATUS OF VISUAL SCIENCE

BY

LEONARD THOMPSON TROLAND

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THE PRESENT STATUS OF VISUAL SCIENCE*

By Leonard Thompson Troland

Chairman, Monograph Subcommittee of the Committee on Physiological Optics, National Research Council

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Chapter I

THE POSITION OF VISUAL OPTICS AMONG THE SCIENCES

Section 1.—Historical Perspective.

The science of visual states and processes rests upon a unique combination of results obtained in three quite widely separated departments of scientific research. As an activity occurring in living organisms and depending upon definite anatomical structures, vision

* The date of writing of the present monograph may be regarded "as of" January, 1921, the literature subsequent to 1920 not being considered. Problems of human vision, only, are discussed.

presents a *physiological* problem. However, the processes in question rest almost entirely upon the action of physical forces, or stimuli, upon the organism and thus demand for their understanding a careful consideration of what *physics* has to say about these stimuli. Finally, regarded as a form of consciousness, vision must be studied by the methods of *psychology,* in which its phenomena are subject to conceptions radically different from those which are employed by either physiology or physics. The history of visual optics shows that although these three points of view have existed side by side from the very earliest times, they have almost never been clearly separated from one another. Even at the present time we are struggling, in visual science, against the ambiguities and misunderstandings which result from a confusion of physical, physiological and psychological conceptions. It is one of the functions of the present monograph to draw distinct lines of demarcation between the domains of these three general sciences in relation to our specific problem, as well as to show in what manner the three sets of facts or hypotheses should be fitted together.

If we go back to the Greek philosophers of the fifth century, B. C.[1], who were apparently the original progenitors of modern science, we find them attempting to explain the phenomena of vision as due to a collision of two streams of particles, the one emitted by objects and the other by the eye, representing respectively the physical and the physiological components of the process. Certain of these early thinkers, however, such as Democritus and Empedocles, also entertained theories of primary and mixed colors, thus entering the field of psychology. The notion of light, or the physical agent in seeing, as a stream of corpuscles emitted from objects was generally accepted by the Greek thinkers and reappears in Newton's corpuscular hypothesis, at the dawn of modern optical science. Aristotle, however, advocated the view that light was an activity of an omnipresent medium which he called the *pellucid,* thus foreshadowing the ether-wave hypothesis of Huyghens. The ancients as a whole, however, were not satisfied with the conception of the organism as being purely passive in the act of seeing and, as exemplified in the optics of Euclid, returned constantly to the hypothesis of an emission of particles from the eye itself. A very few of the ancients, for example Diogenes of Appolonia, recognized the dependency of sight upon the integrity of the optic nerve, and regarded the latter as a channel by which visual impressions were conveyed to the brain.

In the important work of the Arabian physicist and mathematician, Alhazen, near the end of the tenth century, the notion of an emanation from the eye was definitely abandoned and optical problems were

attacked in a fashion similar to that which characterizes the methods of modern physics. Alhazen's understanding of the phenomena of refraction enabled him to explain in a general way the dioptrics of the eye and to conjecture the function of the retina. Alhazen's work was translated into Latin by Vitelo in 1270 but had little influence upon European thought until it was printed, together with an original treatise by the translator, in 1572. This was preceded in time by Leonardo Da Vinci's discussion of color perception, which furnishes the basis for the modern psychological classification of visual qualities, and was followed by physiological discussions of the optical relations between parts of the eye and the principles of binocular vision on the part of Maurolycus of Messina and Giambattista della Porta of Naples. The foundation of modern ideas about vision is probably to be found, however, in Kepler's *Dioptrics,* in which book he develops an intelligible general schema of the process, asserting that "seeing amounts to feeling the stimulation of the retina which is painted with the colored rays of the visible world. The picture," he continues, "must then be transmitted to the brain by a mental current and delivered at the seat of the visual faculties." This general schema, not so different after all from that of Diogenes of Appolonia, was adopted by Newton, whose demonstration in 1672 of the chromatic complexity of white light opened up a great array of problems not only in physical optics but also in physiological and psychological optics. For Newton, however, physical light itself was not endowed with color, but merely with differences in size of the corpuscles which he conceived as constituting it; in common with the metaphysical and psychological philosophers of his time, Newton regarded color as a subjective or secondary quality aroused in the mind only when excitations set up in the optic nerve had reached the brain. Newton's experiments in color-mixture, and his construction on the basis of these observations of the color triangle, would therefore have been interpreted by him in modern terms as being psychophysical in nature.

The eighteenth century, which passed between the publication of Newton's works and the demonstration (in opposition to Newton's ideas) of the wave theory of light by Fresnel and Young, was a philosophical century in which the essential ideas of modern psychology were in the course of development. The empiricists in England, in particular Bishop Berkeley and David Hume, claimed the whole of visual experience as a topic for mental science to consider. Some progress, such as the discovery in 1798 by Sömmerring of the human *fovea centralis,* was made on the physiological side, and substantial additions were contributed to physical and psychophysical

optics by such workers as Lambert. It was not until the beginning of the nineteenth century, however, with the definite establishment of the ideas advanced more than a century before by Huyghens, that rapid progress began to be made either in physical or in physiological optics.

It was at the very dawn of this century that Thomas Young propounded his three-color theory of visual sensations,[2] in which he clearly regarded color and brightness as subjective phenomena produced by the operation of a definitely physiological mechanism. In this view he was opposed by a number of his contemporaries, including the German poet Goethe,[3] who conceived the several colors of the spectrum to be indicative of a corresponding number of kinds of light. The nineteenth century witnessed a rapid increase in our understanding of the eye as an optical instrument, this line of investigation culminating in the great work of Helmholtz, which provides us with a very comprehensive analysis of the dioptric and accessory mechanisms. In the researches of Helmholtz and of his contemporary, Maxwell, the three-color hypothesis of Young[4] became a *working* hypothesis to guide psychophysical research. Both of these great physicists of course adopted the wave theory of the visual stimulus, considered the eye and its nervous appendages as a purely physiological mechanism, and looked upon "color" and "brightness" as sensations evoked in the mind by virtue of the dependency of mental operations upon brain processes. That the psychophysiological point of view was well established early in the nineteenth century is shown by the work on vision of such men as Purkinje[5] and Johannes Müller,[6] the latter being a teacher of Helmholtz and the originator of the doctrine of the specific energies of nerves, according to which sensory quality is dependent not upon the nature of the stimulus but merely upon that of the nerve elements which are set into action. The father of systematic psychophysics and of modern laboratory psychology, Fechner, did some of his earliest work in the realm of physiological optics. A second pupil of Müller, du Bois Reymond, laid the foundations for our modern conceptions of nerve activity and began the physiological study of retinal reactions.

Consequent upon the epoch-making work of Helmholtz, there was a marked acceleration of interest in the problems of vision. For every article or report upon this subject in the years previous to 1860 there are to be found at least thirty in the last years of the century. Unfortunately much of this enormous literature is nearly valueless on account of inaccuracies in the methods which it represents. The most important substantial lines of progress after Helmholtz appear to be the following: the further development of the three-color con-

ception in relation to color-mixture and color-blindness by Arthur König, Johannes von Kries, Sir William Abney, and others; the appearance of the theory of antagonistic colors, propounded by Hering in harmony with suggestions previously made by Da Vinci, Goethe and Mach, which theory attacked the problem of color classification from the psychological rather than from the physical side, thus supplementing the three-color theory from a new angle; the establishment of the so-called duplicity or rod-cone theory of the retina, beginning with the observations in comparative physiology by Schulze and continuing through the work of Boll, Kühne and von Kries; and, finally, advances in our understanding of the principles of visual perception and cerebral localization, including the phenomena of binocular or stereoscopic vision as well as other visual functions which apparently depend upon mechanisms in the brain. Practically all of the multitudinous researches which have contributed to these lines of development have been undertaken from the psychophysical point of view, which regards the processes and contents of our visual experiences as subjective concomitants of physiological operations, the latter being set up by the action of physical stimuli.

In addition to the three fundamental theories which have been mentioned, there has been a vast crop of less popular hypotheses which have attempted to supplement the earlier views either on the psychological or on the physiological side, or to reconcile their conflicting contentions. The most successful of these latter-day hypotheses is apparently that of Mrs. Ladd-Franklin [8] which deals both with the physiological and the psychological data. In the twentieth century, research in vision ceased to be a predominantly Teutonic endeavor and assumed considerable proportions in Anglo-Saxon countries. In America the most scientific work has been done upon the problems of flicker and of the relative brightness sensibility of the eye for different wave-lengths of the spectrum. Apparently the majority of, if not all, American physicists as well as psychologists, have accepted the psychophysical point of view, although defects in terminology have interfered with complete clearness in some of their discussions.

Section 2.—The General Characteristics of Present Visual Knowledge.

As is apparent from the foregoing historical sketch, the special science of vision sustains peculiarly intimate relationships with three general divisions of exact knowledge which are ordinarily regarded as being quite distinct from one another, namely, physics, physiology and

psychology. Text-books of each one of these three general sciences [9] [10] [11] contain chapters on visual phenomena and principles, and although the lines of approach to the subject may differ somewhat in the three texts, the matters presented are approximately the same. Theoretically, this intimacy of relationship with physics, physiology and psychology would be manifested by any science which dealt with processes depending upon organs of external sensation. Actually, however, the greater progress which has been made in our knowledge of visual phenomena as compared with those of other senses and also the striking manner in which the subjective aspects of vision unite themselves with our objective concepts, renders visual optics a relatively unique science in this regard.

In order to clarify our thought concerning visual problems, it is desirable to define clearly the relations which we shall conceive vision to sustain to the three general disciplines under consideration. Physics, physiology and psychology are ordinarily conceived as sciences whose subject-matters overlap relatively little, physics dealing mainly with processes occurring external to the living organism, whereas physiology is concerned with the internal changes which characterize living beings; psychology in its turn dealing with phenomena of mind or consciousness, which are neither physiological nor physical in character. For many practical purposes, distinctions of this sort are adequate, but modern views of the interrelations of the topics which are discussed by the several sciences, as historically laid down, lead to a somewhat more intricate scheme.

Although the movement known as "behaviorism" has in recent times suggested that psychology is, after all, simply a branch of physiology, the great majority of psychologists would define their science as the study of *individual experience,* as it is immediately presented and without hypothesis. Thus conceived, the domain of psychology includes the sensible external world which we find in vision, audition and touch as well as the internal world of bodily feelings and imagery. The world of physics, according to this interpretation of the problem of psychology, is not an immediate datum of experience but is a more or less hypothetical system inferred from experience as an attempt to explain certain aspects of our external perceptions. The physicist's world is reduced to terms of space, mass, and time and certain mysterious electromagnetic concepts, leaving the remainder of the data of immediate experience, such as colors, tones, odors, tastes and the like for the psychologist to consider.[12] Modern physics appears to be concerned mainly with a determination of the plan of a universe built up of ultimate electrical particles, protons and electrons, which combine into a hierarchy of successively more complex, coherent

structures.[13] The simplest type of physical structure is the atom and the most complex type, apparently, is the living organism. Living beings, in other words, are from this point of view to be regarded merely as highly intricate physical mosaics which, in harmony with the so-called mechanistic doctrine in biology, are to be understood entirely in terms which are ultimately reducible to the same fundamental conceptions which reign in molecular and atomic physics.

If we accept this physicochemical conception of life, together with the idea of physics as a general explanatory science which goes beyond the data of immediate experience (while psychology adheres strictly to the latter), we are forced to look upon physiology—the science of vital processes—as being simply a subdivision of physics. Physics (as commonly conceived) and physiology have subject-matters which are homogeneous in general nature, and which are quite distinct from that of psychology. The physiologist is not concerned with his own immediate experiences of living organisms, but with an interpretation of these perceptions in terms of the ideas of physics, while psychology is not interested in such interpretations, but merely in the experiences, *per se*. However, the psychologist finds that a very close correlation exists between these individual experiences and the physical processes which comprise the functions of the given individual organism. I cannot have the experience which I call a color in the space before my eyes unless certain processes are simultaneously occurring within my retina, optic nerve or brain. This is the *psychophysical relationship*, the study of which the psychologist includes, along with that of the nature of experience in itself, among the catalogue of tasks which he has before him.

The remarkable character of this relationship becomes apparent only when we understand clearly the systematic relationships which exist between the several fundamental sciences. As a matter of fact we find ourselves faced in our study of visual facts by a situation which can only be resolved by philosophical or metaphysical considerations. If we waive such considerations as being outside of our domain, the system which we actually have to consider must be described somewhat as follows: There exist two separate, noninterpenetrating worlds, the one, that of any individual's immediate experience and the other that of theoretical physics. The former is made up of such things as colors, tones, temperature feelings, pleasantness and unpleasantness and so on, while the latter consists exclusively of electrical particles arranged and moving in three-dimensional space in accordance with definite mathematical laws of configuration and displacement. However, between these two worlds there exist further mathematical or logical laws of the psychophysical

type, according to which the experience of any individual at any moment is a function (mathematically) of the structures and processes existing at that moment in a certain nervous system, which is said to be the nervous system of the given physical individual. These psychophysical correlations, although believed to be absolutely thoroughgoing and perfect, have no explanation whatsoever outside of metaphysics.

The world of individual experience, as the modern psychologist conceives it, is essentially a spatial world and not a world of pure thought. However, its space does not necessarily have exactly the same mathematical properties as does the space of the physicist's world, and is not included within the latter. The physical system is conceived to be entirely self-sufficient and throughout homogeneous in general nature. Physiology is concerned with certain portions of the physical universe lying primarily within the skins of organisms, but these differ only in *structure,* and not in substance, from the extra-cutaneous facts which the physics of the ordinary text-books considers. Visual psychology is concerned with a certain division of our immediate experiences which comprises what the common-sense individual calls "the external world" as he sees it; visual physiology must deal with the physical processes which occur within the given individual's organism, concomitantly and in correlation with these immediate experiences, while visual physics—in the text-book sense—is concerned with the radiation or "light" which is ordinarily the excitant or stimulus, arousing the organic activities in question.

In spite of the fascinating character of the problems of visual optics and the many avenues of approach which are open for their study, the progress which has thus far been made in the solution of these problems can scarcely be regarded as satisfactory. We have already noted that visual questions have in ancient as well as in modern times aroused a tremendous amount of interest, but also that the great mass of literature which has been produced on this subject contains a relatively low proportion of scientifically valid statements. The symptoms and the causes of this condition are numerous and easy to understand. One of the primary difficulties which is faced by the visual investigator lies in that very psychophysical relationship which we have just been considering. The relation between consciousness and matter has always been a stumbling block for physical and even for psychological thinkers. It is extremely difficult, at least in the past and present states of our conceptions regarding this topic, to separate clearly the psychical and the physical factors in the situation. The physicist tends to employ psychological names for physical realities while, on the other hand, the psychologist often indulges in

what is called the "stimulus error" and describes his sensations or perceptions in terms of their physical conditions. A considerable number of physical thinkers seem absolutely unable to recognize the existence of their own experiences, as such, and inveterately interpret them at the moment of their appearance, in the theoretical terms of their own science. Psychologists and philosophers, themselves, do not agree even at the present time concerning the nature or even the existence of the psychophysical relation. Behaviorists [14] in psychology would banish the psychical from the domain of science, while realists [15] in philosophy are unable to separate the psychical from the physical. This being the situation, it is not surprising that there should be a great deal of confusion in the formulation of problems and a consequent unfruitfulness in the attempted solutions.

Incidental to the confusion which exists concerning the psychophysical nexus, we find a distressing vagueness to be characteristic of many of the concepts which are employed in visual optics. Such a fundamental notion as that of "light," for example, is ambiguous in its denotation. This word is sometimes employed as a synonym of *radiant energy,* whether or not the latter is capable of stimulating the retina; at other times it is used as a synonym of *visible* radiant energy, including only a small range of the total physical spectrum; while in other contexts it stands for the intensity of radiant energy multiplied by its visibility, the latter being a coefficient derived from psychophysical measurements. The word, "color," is equally uncertain in its meaning, standing at one time for a group of qualitative experiences and at another simply for the wave-lengths of radiant energy. Even in its first and psychological use it may refer either exclusively to those visual qualities which possess hue or to *all* visual qualities, including the grays. Similar criticisms apply to other terms which are of common occurrence in visual science such as "brightness," "sensibility," "excitation," and the like. One of the most important forward steps in this field would be the establishment of a definite terminology, based upon a standardized schema of the general system which the science has to consider. Such a revision of terminology has been carried out by the Colorimetry Sub-committee of the Optical Society of America for a restricted field, namely, that of color,[16] and it will be one of the purposes of the present monograph at least to exemplify a consistent schema and terminology for use in visual research.

Another factor which is concerned in the relatively slow progress which has been made by visual optics, is apparent in the diffuseness of the literature dealing with this subject. One hundred and eighty-eight articles published in 1920 dealing with vision were distributed

in fifty-eight different periodicals. These periodicals belonged to such diverse fields as: Physics, physiology, biology, psychology, ophthalmology, zoology, engineering, pathology, surgery, philosophy and general optics. That the acquaintance of specialists in each of these several fields is in general limited to publications in their own journals is indicated by the fact that the various reviews of visual literature which are published annually appear to cover little beyond the journals belonging in the reviewers' own natural fields, the selection of articles thus obtained being practically always a small fraction of the total.[17] This diffuseness of the literature is reflected by the methods and conceptions employed by investigators publishing in the several fields, each showing a lack of acquaintance with the problems and results with which the others are concerned.

This state of affairs is not only symptomatic of a lack of organization and general enlightenment among individuals working upon visual problems, but tends to perpetuate the conditions in question. Every year sees the publication of a number of serious papers treating problems which have already been dealt with satisfactorily, far beyond the point reached by the writers of the papers in question, these writers exhibiting complete ignorance, or at least lack of understanding, of the accepted principles which apply to their problems. The field of visual research is certainly one which is ripe for coördination of ideas and investigations. Unlike the case in some other departments of science, our visual conceptions and theories are sufficiently well formed to make possible a semi-coherent view of the whole field of investigation, and yet at the same time are sufficiently vague and inconsistent to permit unguided individual minds to go sadly astray. It is one of the functions of the present monograph to indicate schematically the fundamental conceptions and principles of the science in a system which embraces—at least potentially—all of the diverse interests which are concerned.

A further obstacle to progress in our knowledge of vision lies clearly in the inherent *complexity of the subject-matter.* On the psychological side, our visual experiences are far more intricate and varied than in any other department of sensation, perception or imagination. Although many aspects of visual experience are inherently capable of clear treatment, the history of subjective visual analysis shows that it is very easy to misunderstand essential facts and to omit from our systematic descriptions, data which are of fundamental importance. Witness, for example, the divergence which exists between various psychological color systems, or between extant theories of visual space. On the physiological side, the enormous complexities of the retina and

of the visual cerebral cortex stagger the scientific imagination and frighten us often into a mental condition in which we look upon all visual hypotheses as mere pedagogic devices. The failure of the majority of visual theories, so-called, to recognize the inevitable complexity of the visual process on the physiological side is responsible at once for the unfruitfulness of these theories and for our inability to decide among them.

The history of physical science at large shows that it is an essential of progress that we should possess hypotheses by means of which to coördinate the vast mass of data which is educed. In general physics these hypotheses can very often be of a simple nature. However, in physiology, and in particular in nerve physiology, it is extremely doubtful whether any simple hypothesis can be true.[18] Physiological mechanisms are often found, when actually demonstrated, to be even redundantly complex. The majority of visual hypotheses have lacked definiteness because of their failure to formulate explicitly the relations suposed to hold between the mechanisms, which they describe, and the demonstrable anatomical or physiological components of the visual nervous system. This is a topic which we shall consider in further detail below. Even the physics of the visual stimulus is at the present moment in a state of theoretical confusion and indecision. Although the wave theory of radiant energy retains its prestige the quantum conception, which makes the emission and absorption of such waves discontinuous, has raised fundamental questions which have thus far remained unanswered. It seems inevitable that these changes in physical optical theory should have an influence upon our final conception of the visual process as a whole. New hypotheses of retinal response based upon the quantum notion in general physics have already begun to appear.[19]

Our survey of the position of visual science in the general system of scientific knowledge reveals the former discipline as a fundamentally important, much pursued, but a relatively disorganized endeavor. On the side of psychology, our knowledge of vision comprises what is probably the largest and most positive single chapter in mental science. On the side of physics, in the domain of physiology, many positive facts concerning the sense-organs and the central mechanism have been established. In the domain of physical optics, in spite of the difficulties raised by the quantum theory, tremendous advances have been made. Many definite psychophysical principles connecting the stimulus, the sense-organ processes and even the central processes with immediate experience or consciousness have been established. Still, the science as a whole seems unduly fragmentary and chaotic.

It would appear that a coördination of ideas among the multitudinous investigators, followed by a series of systematic attacks upon really crucial questions, should prove more fruitful in this domain than in any other with which we are at present acquainted. Such coördination of thought would naturally involve a careful reconsideration of all accumulated authentic data in the light of the many and varied hypotheses which have been advanced to synthesize these data, and should lead ultimately to a reconstruction of these hypotheses which would provide us with a definite, satisfactory, theoretical account of the facts which we know. It will be possible in the present monograph only imperfectly and schematically to suggest some of the factors involved in such a reorganization of visual science.

CHAPTER II.

THE FUNDAMENTAL CONCEPTIONS AND METHODS OF VISUAL SCIENCE

SECTION 3.—THE ULTIMATE FACTORS IN THE PROBLEM OF VISION.

If we adopt the conceptions which have been suggested in the foregoing introductory discussion, we can divide the total system of facts with which visual science is concerned into two general, non-overlapping, groups. These are the psychological and the physical facts respectively. The *physical* group of factors will include not only radiation and other possible stimuli to vision, but also all *physiological* factors, which are simply a special combination of ultimately physical objects, or activities. We may unite all of the physical factors thus defined into a single coherent mechanism to be called *visual response,* which is a mechanism involving the *propagation* of a chain of physical influences, starting with an object and passing through a long line of conductors to terminate in some sort of mechanical or chemical readjustment of a living organism to its environment. We shall conceive this mechanism to be throughout, and in its entirety, reducible to the ultimate terms of modern theoretical physics.

The psychological group of facts, on the other hand, must stand entirely by itself. Its terms are not reducible in any sense either to those of classical physiology or to those of modern theoretical physics. The visual constituents of individual consciousness, human or otherwise, can only be *described* and, by definition, are not susceptible of interpretation or reduction to other terms. If what we mean by color, for example, is a quality, or group of qualities, which is actually given in our individual visual experiences, it is clear that color cannot be reduced to wave-lengths or to any other unit simpler than itself. Color is an ultimate constituent in visual consciousness. Exactly similar considerations apply to other psychical factors in vision, such as the depth elements in various optic perceptions. Although certain philosophical theories endeavor to identify visual space with physical space, such an identification is not permissible in strictly scientific thinking because we possess no positive means for demonstrating its validity. The only safe course, therefore, is to regard visual experience in all its qualitative, spatial and temporal aspects, exactly as it is given, as a system by itself, completely set over against the physical system which comprises the stimuli and the reactions of any neuromuscular organism.

Let us consider briefly the respective constitutions of these two opposed, but correlated, systems.

Visual Experience.—Psychologists and philosophers have in the past entertained a variety of more or less discordant definitions of psychical concepts such as consciousness, mind, experience, etc. The most primitive definitions would formulate all psychical conceptions in terms of a *relation of awareness,* sustained by a subject or ego to objects in the physical world. However, this manner of conceiving psychology's subject-matter is based logically, as well as historically, upon a doctrine which has long been rejected scientifically, namely, the hypothesis of the soul. Accordingly, practically all modern psycologists agree that psychical conceptions cannot in general be defined in terms of relations involving either subjects or objects, but must be regarded in quite the same general way in which physics considers its fundamental terms. The leading idea of modern psychology is that of *consciousness,* and this consciousness is not a relation of awareness but is a *mosaic* involving the structural combination of irreducible and self-sufficient elements.[20] These elements are simply the actual given data of any individual man's experience, and consciousness itself is simply any instantaneous phase of such an experience.

Although the conception of consciousness which is thus established renders it the most concrete and real of all possible notions, it is nevertheless difficult for the physically-minded thinker to grasp the idea. This difficulty arises from the influence upon his thought of a number of hidden premises and misconceptions. In the first place, he is accustomed in his habits of thinking to regard given components of his visual experience as being identical with certain aspects, at least, of physical objects. We do not ordinarily conceive of a book which we may perceive in front of us in space on a table, as being a component of our visual consciousness but rather tend to identify consciousness with the fact "that we see the book." A moment's consideration, however, will show that the process of *seeing* the book must be described in physical and physiological terms, the only distinctly psychological fact being the perceived book itself, in its given relationship to other constituents of our visual consciousness. It is also evident that the book as perceived is not a physical configuration of electrons and protons, or even of atoms and molecules, but is quite a different thing inherently, namely, a system of color surfaces arranged in a three-dimensional space, and even further it may be noted that the arrangement of these surfaces follows certain principles of perspective which are required by the nature of visual space, but which are not characteristic of physical space.[21] The physical book in itself has no perspectives, this property being in physics only a characteristic of relations obtaining between a book and images, or "projections," which

may be formed, more or less in its likeness, in portions of space different from those which are occupied by the book itself.

A careful study of this situation should suffice ultimately to make clear both to the physical scientist and to the layman the distinction between the physical objects which are concerned in vision and those immediate components of visual experience which the psychologists call perceptions or sensations. The task of modern psychology in relation to vision, as to all other departments of experience, consists primarily in a bare description of the data of individual experience exactly as they are presented, without inference or hypothesis. Although this task may seem direct and simple, it is in point of fact difficult of attainment and complex in its results. The reason for this lies in the inveterate tendency of the physical and common-sense intellect to employ the immediate data of experience merely as symbols of something lying outside of that particular experience. Even pleasure and pain are usually regarded in this light, and in everyday life it is only in an aesthetic mood that we appreciate the nature of color experiences in their own right. The physicist, peering into a spectroscope *has* a band of color in his experience, but believes that he *sees* a certain wave-length distribution of radiant energy. For the purposes of his physical thinking, this belief regarding the cause of his momentary experience is the only thing which concerns him, so that he entirely neglects to consider experience in and for itself. The psychologist, on the other hand, restricts himself rigidly to exactly what he finds within his experience, weeding out resolutely all references to its possible causes or implications. By so doing he gets back to the inevitable foundation of all empirical thinking and arrives at an account of certain absolutely indubitable realities of science.

If we assume the psychologist's standpoint, thus defined, what will be the main results for the science of vision?

In attempting to answer this question we must note in the first place that any individual's consciousness is at any moment a rather closely knit system. This does not mean that it is absolutely unitary or simple, for in this case it would be quite impossible to analyze it, but it does imply a certain difficulty in drawing sharp lines of demarcation within it. This is particularly the case if we desire these lines of the division to correspond with similar partitions which we may later set up in the physical or physiological system of *response*. We can limit roughly the boundaries of vision within consciousness as a whole by noting the domain of consciousness which is influenced by the act of closing or opening the eyes. We may define this latter act if we wish in psychological terms by reference to the tactual and muscular sensations which accompany it, or on the other hand we may describe it in

physical terms as a process regulating the incidence of radiation upon the cornea. Having once had our attention drawn to this particular realm of experience as opposed to other divisions, such as the tactual and the auditory, we can recognize its distinctive, coherent character and the relatively homogeneous nature of the elements which comprise it; and we can proceed, therefore, to enumerate these elements and to describe analytically the various mosaics in which they are from time to time manifested. However, should we become interested in the physiological determinants of these elements and structures, we should probably discover that they are not all to be found in the ocular mechanism, much less in the receptor processes of the retina. On the other hand, if we attempted to define the visual section of experience in terms of its ocular conditions we would obviously rule out some aspects of vision as subjectively delimited, and at the same time would probably be led to include experiential characteristics which introspection would not link in any way with the eye.

In this situation, since the delimitation of a certain segment of experience as visual is logically an arbitrary affair, we shall be wise if we make the boundaries of visual experience quite flexible and readjust them from time to time, in the light of progress not only in introspective psychology but in physiology and psychophysiology. Such readjustments, however, will in all probability involve only relatively small corrections of an original definition based upon the experiment of closing the eyes. When the eyes are closed, visual experience, although radically modified and simplified, is by no means eradicated. The visual field is still present but its constituents are relatively homogeneous and lacking in stereoscopic character. However, faint patterns of colors constituting images or after-images, idioretinal whirlings and the like, may be present. We also experience tactual or kinaesthetic sensations which are referred to the pressure of the eyeball against the lid or to the palpebral muscles, and we localize these sensations approximately in coincidence with the residual visual experience. In general, as long as we retain any visual field at all we are able to localize within it non-visual sensations such as those of touch and hearing, but when the visual experiences themselves are cut off or reduced, the other qualities remain and are then forced to make up their own spatial system.

The direct introspective analysis of visual experience, as thus approximately delimited, indicates that its main constituents are of two general sorts, namely, colors and depth elements. Visual experience as a whole is a three-dimensional manifold of the spatial type involving the simultaneous colligation of a large number of discriminable elements, although in general these elements are united into a

continuum. The three fundamental directions of visual space are not, like those of physical space, identical in their properties but are distinguished from one another by definite peculiarities. The depth elements may be regarded as arranged in radial lines converging upon the empirical eye while the color elements tend to be disposed more or less at right angles to these radii in the form of surfaces or two-dimensional patterns. In general, the lines of depth elements tend to terminate at the color surfaces which they intersect, and every such line of depth components must extend to such a color surface. The differences in pattern between various visual experiences depend upon the disposition of colors of various kinds within this three-dimensional manifold. We shall consider some of the results of purely psychological analysis in vision more in detail below, the function of our present discussion being simply to make clear by concrete as well as abstract references the actual subject matter which the psychology of vision must consider.

The Schematic Analysis of Visual Response.—Having indicated briefly the distinctive character of the psychological topics involved in visual science, let us now turn to consider the second group of facts in the case, which, it will be remembered, we conceive to lie completely outside of any given visual experience. When we look about for a general name for the set of physical factors which are involved, eliminating carefully all connotation of the psychical aspects of vision, we find the most appropriate term to be the word "response." This term is often employed to designate merely muscular reactions but is used more broadly for all physiological activities which can be represented as effects of preceding stimuli. Our present application of the term will involve a slight extension even of this broader significance, so that what we shall designate as the response system in vision will include not only the afferent and efferent processes of the neuro-muscular mechanism but also the specific objects and stimuli which set off these processes or with respect to which they are regulated. The excuse for thus including the physical object and stimulus lies in the fact that from a general physical point of view they constitute integral parts of a continuous chain of events or of concatenated mechanisms. To distinguish sharply between the physiological and environmental factors in the process is to lay undue stress upon the significance of organic boundaries and to succumb to a semi-vitalistic tendency. When the radiation which is emitted from the object passes through the epithelium of the cornea, no essential discontinuity is introduced into the process, and even when the radiation impinges upon the retinal receptors—therein exciting photochemical changes—the discontinuity is not greater than that which demarcates nervous and

muscular processes or on the other hand the propagation of radiant energy from its emission. We shall obtain the most helpful view of the entire situation if we group the various factors together because of their close causal interrelationships, rather than separate them in conformity with preconceived physiological classifications.

Defining the response system in this way, we find that it presents a special instance of a general class of physical processes known as *propagations,* which consist of a series of corresponding events successively displaced with respect to one another in both space and time. A general list of such successive events which we may expect to find in any example of response, visual or non-visual, would include the following, enumerated in the order of their occurrence and dependency: (1) The physical object, (2) the stimulus, (3) the sense-organ process, (4) the receptor process, (5) the afferent nerve stimulation, (6) the afferent nerve conduction, (7) the central synaptic, or adjustor process, (8) the efferent nerve conduction, (9) the end-plate process, (10) the effector process, (11) the effect. Each one of these successive stages may be regarded as the effect of the preceding stage. In any actual instance, as a rule, each of the stages is capable of subdivision into a number of sub-stages which have a serial dependence upon one another just as have the main stages with respect to one another. In vision, for example, the sense-organ process involves successive refractions of radiation at the considerable number of dioptric surfaces which are involved in the structure of the eye, each one of these refractive operations being forced to deal with the results of the just preceding operation.

We may now consider briefly the concrete exemplifications of these successive stages which are given in the case of visual response.

(1) The first stage in the visual response process, the *object,* is of course in its most complete form simply a physical body as conceived by the modern physicist. As such it must consist in a specific geometrical configuration of positive and negative electrical particles known as protons and electrons, which undergo certain continuous or possibly spasmodic motions. Such a physical object can have no color or other visual properties in itself. It must, however, possess certain definite physical characteristics in order to become "visible," and hence to enter into a visual response. These characteristics are clearly those which enable it to emit radiant energy of wave-length and intensity composition such as to act upon the retina of the eye. Moreover, in order that the object should enter into the visual process, the centers of emission of such radiation must be so placed in space with respect to the eye and other absorbing media as to permit the radiation actually to reach the retina. We might, therefore, define a visible

object somewhat abstractedly as a geometrical arrangement of points from which are emitted streams of radiation capable of reaching and stimulating the retina. This definition would in general render the visible object a configuration of radiation capable of being projected through a relatively non-absorbing medium upon the eye of an observer. It would make real optical images as well as luminous and reflecting bodies constitute visible objects. Virtual images, however, would not be visible objects because of their purely imaginary or projective character.

(2) It is apparently impossible to define a stimulus without reference to the organ or process which is stimulated. Accordingly we cannot define the *visual stimulus* simply as radiant energy in general but must restrict it to radiant energy of wave-lengths and intensities such that it can excite the retinal receptors. Radiation possessing this power has commonly been called "light," but in view of the development of modern photometric concepts,[22] it seems advisable to reserve the term, light, for a somewhat different meaning and to describe the stimulus to vision as *visible radiation.* The facts which are summarized in the visibility curve show that the visibility of radiant energy varies continuously from one wave-length to another, so that it is impossible to specify rigidly the limiting wave-lengths outside of which radiant energy ceases to be a visual stimulus. We can only assert that the claim of any sample of radiant energy to be regarded as such a stimulus is valid in proportion to its visibility, being maximal for a wave-length of 556 millimicrons and falling off to 1/100 of this value on either side at wave lengths 429 to 687 millimicrons, respectively[23]. It is clear that in order to be a visual stimulus, radiant energy must not only possess the appropriate wave-lengths and intensities but must impinge upon the eye in such a manner as to enter the pupil and fall upon a sensitive portion of the retina.

(3) The *sense-organ process* in visual response will be conceived to comprise all of the changes which are undergone by the streams of radiant energy, from the moment when they impinge upon the cornea until they are absorbed by the sensitive retinal elements. These simultaneous as well as successive modifications of the stimulus, involve not only refraction of the rays but such further changes as absorption and scattering. The iris intercepts varying proportions of the incident radiation and the defects in transparency of the ocular media introduce local and general aberrations of the rays from their ideal paths. Moreover, the aqueous substance and the pigment material of the eye possess selective absorption characteristics which modify the distribution of intensity of the radiation among different wave-

lengths. We must include in the sense-organ process not only useful or functional changes which are undergone by the radiant energy but also adventitious effects, such as those of chromatic aberration and the causes of many biologically undesirable entoptic phenomena.

(4) On account of the crucial importance of the essential processes in the retina by which the radiant energy becomes a nerve stimulus, it seems justifiable to separate them logically from the preceding factors in the sense-organ activities. There is now practically no doubt that these so-called *receptor processes* occur in the terminal segments of the rod and cone cells and it is highly probable that they are photochemical in nature. It is necessary to suppose that within the substance of the rods and the cones, radiant energy is absorbed and is converted into energy of some other type capable of initiating a nerve current within the conducting segments of the rod and cone cells.

(5) The process by which the receptor effects are *transformed into a nerve current* must in all probability be regarded as a distinct stage in the response chain. If the receptor action is photochemical we must understand how such a process arouses a nerve impulse, which is of quite a different character. There is at the present time every reason for believing that all nerve currents are periodic or pulsatory in nature, and it is necessary to explain the generation of such intermittent effects on the basis of a continuous activity within the receptor cells.

(6) It is to be supposed that the transition from receptor reaction to nerve current takes place within the rod and cone cells themselves and that all that is required is a propagation of the nerve activity, thus initiated, along the conducting elements of the retina, the optic nerve, and the optic tract to the brain centers. However, it is to be noted that in the case of visual response this *afferent conduction* is a complex affair. Within the retina itself, three individual neurones, or individual conducting units, are involved (including the rod and cone cells) and consequently even within the retina there are two points of transfer between neurones and hence two characteristic *synaptic* processes. These intra-retinal transfers involve, in the majority of instances, the condensation or unification of a plurality of currents starting in separate receptors. Moreover, the amacrine cells of the retina provide cross-connections between more or less distant lines of conduction. When the separate lines of neural propagation have passed radially into the nerve fiber stratum of the retina they move along the face of the retina to converge upon the papilla, or point of exit of the optic nerve. In the latter portion of their paths they travel within continuous nerve conductors which carry them uninterruptedly

to certain nuclei of the mid-brain, located in the anterior corpora quadrigemina or the external corpora geniculata, as the case may be. At these points, however, new synaptic transfers take place which probably involve a convergence of currents from corresponding points of the two retinas, as made possible by the semi-decussation which occurs at the optic chiasma. The impulses now pass towards the higher centers along two paths, on either side of the brain. The more important pair of these for visual experience, or for the higher cerebral processes, is probably constituted by the two central visual tracts, the fibers of which end in the visual cortex of the cerebrum. The alternative pair of paths passes to the oculomotor nuclei where they connect with outgoing fibers of the third or oculomotor nerve which controls the pupil, the ciliary muscles of accommodation, the majority of the external muscles of the eye, and the muscles of the lid. The oculomotor and other nuclei which are connected with the third, fourth and sixth cranial nerves, respectively, receive efferent fibers from the cerebral cortex, these latter fibers being concerned in voluntary movements of the eyes.

(7) It is clear from the foregoing that the *central or adjustor process* in visual response also is very complex, there being a considerable number of nerve centers at different levels which are simultaneously operative. A central process may be said to occur at any junction point between an afferent and efferent neurone, but it is not always easy to decide whether nervous elements in the brain are afferent or efferent, some of them—of the association type—apparently falling into an intermediate class. However, even if we assume a sharp separation between afferent and efferent elements we are forced to recognize the existence of a multiplicity of central processes in vision, transfer of the visual currents from the sensory to the motor side of the response occurring at a series of successively higher levels. If we are interested in the automatic motor adjustments of the eyes we shall be forced to consider such central transfer processes occurring in the mid-brain and can neglect the cerebral activities. On the other hand, if our concern is with voluntary adjustments we shall be forced to study the synaptic processes of the cerebral cortex; say, for example, those occurring in the visual projection areas within the cuneus, in the occipital lobe of the cerebrum. Voluntary adjustments, however, appear to be of several grades, some of them involving activities in the frontal and other association regions of the cortex. It is not legitimate in a purely physiological discussion to define the central process as the one which directly determines visual experience, particularly since at the outset of our investigation we have no proof that this experience is uniquely related to any single stage of the response.

(8) In visual, as in practically all other forms of response which involve the higher nerve centers, the exact form of the *efferent nerve conduction* is extremely variable. If we confine our attention to the transfer of nerve currents through sub-cortical centers, the efferent results are fairly specific, leading to definite innervations of the oculomotor apparatus, the muscles of the lid, the internal and external muscular apparatus of the eye-ball, etc. In such sub-cortically mediated responses it is usually possible to predict the course of the efferent innervation from a knowledge of the character of the afferent nerve currents, innervation of the pupillary sphincter increasing with the intensity of the afferent current; or the excitation of the external ocular muscles being regulated in correspondence with the position of the stimulus on the retinal field, etc. The outcome of responses which pass through the cortex, on the other hand, depends radically upon the associative setting of the cortical conduction paths, and this setting varies in such a way as to make possible not only oculomotor adjustments but any conceivable innervation of the efferent nerves which supply the striped muscles, or even indirectly the unstriped muscles of the body. Whether or not a particular reaction of these efferent mechanisms is to be regarded as visual must depend upon an analysis of the afferent factors which are involved in the particular instance.

(9) The so-called *end-plate process* is a characteristic activity which takes place between the efferent or outgoing nerve current and the effector reaction, which latter may be a change in muscular contraction, in glandular secretion, or in the excitation of an electric organ. The existence of an intermediary process at this position in the response arc has been definitely established and may in the future prove to play an important rôle in our complete understanding of the total response mechanism.

(10) The *effector process*, as above indicated, is not inevitably a muscular contraction. Even if the result is confined to a motor apparatus it may consist of relaxation (inhibition) rather than of contraction. It would also appear advisable to include under this general designation not only changes but also neurally maintained states of tonus or steady excitation in the effector apparatus. Such maintained conditions, or postures, naturally depend upon the continuous operation of the total response mechanism in a definite manner. We may also include in the effector stage of the response, movements of non-muscular organs—such as the eyeball or portions of the skeleton—which result from muscular contraction or relaxation, as well as postures of the organs in question which accompany steady states of the muscular apparatus.

(11) The final stage in the response, which we have called *the effect,* of course varies as a function of the effector action. As a rule the effect involves some change in the relation between the organism and its environment, and this change is reflected by an alteration of the stimulus which is operative in the given response arc. In this way the whole process becomes cyclic, each succeeding wave of the response activity reacting via the environment upon its successor. Thus movements of the body as a whole, of the head, or of the eyeball, change the pattern of stimulation of the retina, or fixed postures operate to maintain this pattern.

If we analyze visual response in a purely physical manner, as we have done schematically above, we see that at no point does it involve any psychological or experiential factors. If we adhere to a mechanistic biology we cannot legitimately explain any of the response activities, no matter how complex or variable they may be, in psychological terms. The ordinary textbook of physiology, in discussing visual processes, makes a very considerable use of psychological concepts, particularly in the consideration of such matters as retinal sensibility and binocular vision. This is due in part to vagueness in the delimitation of the boundaries of physiology by the authors of these books, but is excused by our lack of understanding of the processes in question in strictly physiological terms. When such understanding has been achieved, physiologists will spontaneously dispense with their psychological references and will reduce their accounts to terms which involve no psychological factors and which rest wholly upon the fundamental notions of physics.

The Psychophysical Relation in Vision.—To say that reference to psychological elements or processes is not required in an ultimate account of visual response is clearly not tantamount to a denial of the existence of such elements and processes. It also does not imply that the latter are without relation to the response mechanism. The doctrine of psychophysical parallelism, which is employed as a working assumption by all conservative psychologists, affirms not only the concomitant existence of the physiological and the psychological systems, but postulates a rigid law of interdetermination without interaction as holding between the two systems.[24] Each system is explicable only in its own terms, but the two systems together constitute a more comprehensive scheme, with new sets of laws which are known as *psychophysical,* and which must be included in any account of vision or other psychophysical processes if the account is to be complete.

We have already seen in our introductory discussion what are the general relations holding between psychology, physics and physiology

and between their respective subject-matters. The visual experience of any individual, A, at any time, t, is regarded as existing completely outside of the visual response processes of this same individual at the given instant. The experiences can be described only in psychological terms, while the analysis of the concomitant response must be made in exclusively physical terms. Theoretically, a complete causal explanation of the response activities can be given without reference to the psychological description. Apparently, however, a complete causal understanding of the visual experience is not possible on the basis of introspection alone. In this respect the two sets of data, the physiological and the psychological, are lacking in symmetry; a relationship which suggests that although the physiological activities do not depend upon the psychical ones the reverse statement is not true, the psychical factors being determined, at least in part, by corresponding physiological variables. A careful analysis of the situation, however, shows that this is not ultimately the most plausible interpretation of the whole system of facts, although it develops no great difficulties as a working hypothesis.

If we restrict ourselves to the doctrine of psychophysical parallelism, we must suppose in the first instance merely that the psychological factors can be represented as mathematical or logical functions of certain of the physiological factors. This conception does not imply the possibility of interaction—transfer of energy or a reaction of forces between the two systems—but represents simply the general possibility of formulating laws or equations by means of which the nature of the psychical system can always be predicted from a knowledge of its corresponding physiological or physical system. The laws of this correspondence, when they are ascertained, comprise psychophysiological science.

The physiological psychologist assumes that the determinative interrelationship of experience and response is perfect, that is, that the correlation between the two systems is logically rigid. Although this assumption cannot be completely validated, otherwise than by a finished science of psychophysiology, it is the most encouraging hypothesis to employ in endeavoring to work out such a science. The supposition of this perfect correlation between the psychical and the physiological, however, does not imply that *all* of the stages and the components in the response system are directly involved, or, if they are not, exactly what selection of physiological factors must be made. Just as soon as we face the problem of the exact type of correlation which may exist between a relatively simple system like visual experience and the enormously complicated mechanism of visual response, we realize that in all probability only a small fraction of the latter

system is actually involved in the determination of the former. This probability becomes a certainty when we study the results of definite psychophysical experiments. Our visual experience seems in every-day life to be correlated most closely with the first, or object stage, of the response activity; unless the experience is faithful to the object we do not ordinarily say that we have *seen* the object at all. A visual hallucination or illusion is not a complete process of sight but is a subjective or psychological phenomenon only. However, this naïve belief in the direct dependency of our visual consciousness upon objects is sadly upset as soon as we begin to experiment, or even to reflect upon certain commonplace observations. The effect upon experience of closing the eyes demonstrates at once the essential importance of the subcutaneous or infra-organic stages in the response mechanism. Closing the eyes involves a cutting-off of the visual stimulus, radiation, just as it is about to pass through the cornea. We find that such an interruption of the response at any stage between the object and the highest central activity in the cerebral cortex has a generally similar result in experience, whether such interruption be prior to or subsequent to the incidence of the stimulus upon the sense-organ. Visual experience is modified and reduced even more radically by interfering with the response activity in the cortical projection areas than it is by interrupting the optic nerve currents, or by destroying the retina. If we test the efferent side of the response, we find that the results in experience of interference with the physiological mechanism are of minor importance except for their influence upon subsequent afferent activities. When we interfere with the motor adjustment of the eyes or of the body as a whole we of course modify the stimulus and in that way obtain a change in consciousness. However, if these secondary effects are ruled out, it appears that there is very little correlation between any efferent component of the response system and experience. From such considerations we arrive at the general conclusion that what may be called the *direct determinants* of visual consciousness lie on the afferent-to-central side of the response arc exclusively.

This result, however, still leaves the question undecided whether all, or only a selection, of the afferent and central factors are concerned. On the basis of the given facts, it is inconceivable that visual experience should be correlated *exclusively* with any stage of the response except the most central one, since cutting off the central stage is capable of modifying radically and even of obliterating visual consciousness. However, it is quite conceivable that consciousness should be correlated simultaneously and directly with all of the afferent and central stages, since it appears that modification in any one of these

stages is capable of evoking a modification in experience. A simple explanation of the given facts, however, would consist in the view that the experience is correlated with the central process alone and sustains a determinative relationship with prior stages in the response, simply because of the dependency of the central process upon these more afferent activities. In order to choose between these two alternative explanations we must make experiments in which characteristic processes in the various stages are reproduced in the absence of their normal causes or concomitants in other stages. If we should find that all forms of visual experience can be evoked through an artificial reconstruction of characteristic processes in a single stage alone this would tend to prove the unique significance of the stage in question for psychophysiology. It is of course difficult to accomplish such artificial reproduction of isolated response stage activities, but in certain pathological conditions nature has apparently come to our assistance in this regard. Observations upon these pathological states indicate strongly that cerebral processes alone are responsible for the totality of all visual experiences, the apparent dependency of these experiences upon more afferent stages in the response being an outcome of the influences which these latter stages ordinarily exert upon the cortical activities.

This argument would lead to a doctrine which may be called that of the *cerebral determination of visual experience.* In a more familiar terminology this would be equivalent to stating that the "seat" of visual consciousness is in the brain. However, we should be very careful to realize that visual experience is not and cannot be localized within any part of the nervous system, the cortex being not the seat of consciousness but only the seat of variables of which consciousness is representable as a function. It would be much harder for the visual consciousness to pass through the eye of man than for a camel to go through the eye of a needle, and this translation cannot even be conceived to have occurred from inward outwardly in an act which is ordinarily described as "projection." If such a projective activity actually occurs it must *create* visual experience in an external world of space and not merely place it there. We can readily conceive of the brain as forming part of visual experience, but to thrust the experience into the brain is psychophysically impossible. Such confusions as are involved in common-sense discussions of these subjects seem inexcusable in a scientific analysis, where we must realize that the physiological and the psychological systems are discrete and incommensurable mosaics, which have no actual connection and merely exhibit a formal correspondence. On account of our habits of thought,

this may be a difficult doctrine to apply, but experience has shown that it is the only one which, upon a non-metaphysical level of argument, can lead us to really intelligible conclusions.

Although data now at hand make it highly probable that visual experience is correlated directly only with cerebral activities, it is by no means certain where these activities are located within the cerebral cortex. They are ordinarily conceived to lie in the visual projection area of the occipital lobe, since it has been shown that definite disturbances of consciousness appear as a consequence of specific disorders in this region. However, other facts show that still higher cortical activities are involved, since visual imagery is dependent upon the integrity of the so-called visuo-psychic areas which surround the projection surfaces, and the derangements of vision which occur in hysteria and other allied psychoses demonstrate a dependency of visual experience upon the higher association areas of the cortex.[25] The simplest working hypothesis would be that the direct determinants or correlates of visual experience are to be found only in the higher association area activities of the cerebrum, these activities being quite directly under the domination of projection area processes and influenced *via* these processes by the whole afferent chain. This conception would enable us to explain all of the relationships which we find to obtain between the various afferent and efferent stages of the response, without involving us in a complex psychophysical formula which makes the visual consciousness a function simultaneously and directly of a plurality of response stages. It is true that if visual consciousness is linked logically with the most central or focal, cortical, activities, it must bear an *indirect* determinative relationship to all of the other stages in the response. These indirect relationships, however, are not, properly speaking, psychophysical and are only to be understood by a combination of purely physiological principles with direct psychophysical laws.

Unfortunately, we are not at present in a position to study with ease these direct psychophysical interrelations, and so we are forced to consider indirect relations which in all probability involve complex physiological transformations. The factors in the response which are most amenable to observation or experiment are naturally the object, the stimulus and the sense-organ stages. The study of the indirect relationship which obtains between visual experience and the first three or four stages in the response, up to and including the receptor process, constitutes the science of *visual sensation.* Sensation, as thus defined, is not an element of experience, but is a relation between experience and the receptor process, with its accessories. It is very

common in psychological discussion to define a sensation merely as an element in consciousness, but since the word implies a reference to an organ of sense, it seems advisable to restrict its use to a psychophysical meaning. Color and elements of visual depth are ultimate components of visual consciousness, but whether or not they are regarded as sensations will depend upon whether in the particular instance under consideration they can be shown to rest indirectly upon a stimulus and a receptor excitation. Strictly speaking, a sensation would be defined as a "partial derivative" of consciousness with respect to variables lying in the stimulus and the sense-organ or receptor process.

Sensation is not the only chapter in the indirect psychophysics of vision, as additional chapters present themselves in the study of *visual perception* and *visual action.* The former may be defined in terms of the relation between consciousness and the first or object stage in the response system. Perception represents, so to speak, the effort of consciousness to duplicate or at least to represent the object. The machinery of this effort, of course, lies in the brain, but its operations are dictated by influences emanating from the object itself, although these influences are not carried exclusively by the vehicles which are offered by a single eye in any single act of visual response. The formation of visual object consciousness in three dimensions by the addition of the depth factor to that of color, rests upon a very complex foundation. Probably the most important components of the latter consist in the relations between the images formed upon the two retinas, respectively. The combination of the two groups of retinal impressions to produce stereoscopic vision, however, probably requires support by kinaesthetic factors derived from the receptors of the oculomotor apparatus which represent the state of convergence of the two lines of sight at any moment. The functioning of this binocular mechanism, however, certainly depends upon an association of its data with the results of experience or past impressions, made through other sense channels, such as those of general bodily kinaesthesis and of touch, an association which permits various degrees of disparation between the retinal images to become a symbol or an index of the distances and solid conformations of objects. Such general experience records, also, can be combined with qualitative characteristics of even monocular excitation, which are employed as so-called "secondary criteria" of the third dimension. Illustrations of the latter are apparent size of familiar objects, atmosphere, relation to the horizon, covering of one object by another, etc. Although the combination of these multitudinous factors in relation to the inherently simple visual consciousness is directed toward a valid representation of the object,

the mechanism of this combination clearly lies, not in the object nor even in the sensory apparatus, but in the intricate central processes which intervene between the afferent nerve conduction and the processes in the cerebral cortex which immediately determine the visual consciousness.

This synthesis of sensory impulses by the brain is directed functionally toward the regulation of the motor apparatus of the body. Such regulation in turn is useful biologically because it adapts or adjusts the organism to the object. It is for this reason that the central activities must possess a reliable correlation with the exact nature of the object itself. As we have previously indicated, the efferent side of visual response is not necessarily confined to oculomotor adjustments, although such adjustments normally accompany all visual processes. We must also include efferent innervations of any muscular or glandular systems in the body which depend, in given instances, for their regulation upon visual stimuli. We have also seen that the efferent factors in the visual response are not seemingly to be counted among the determinants of the visual consciousness. However, the relation may be turned about and the visual consciousness be regarded as one of the determinants of the efferent innervations. Such an apparent relationship would evidently follow from the correlation of the consciousness directly with the highest central process, since this latter process is responsible for the outgoing nerve currents. The relationship in question clearly makes it possible to study an indirect psychophysical connection between visual consciousness and the evident motor activities or behavior of the organism. The study of this set of interdependences is that of *visual action.*

It will be obvious that many ramifications of the three general indirect psychophysical aspects of vision above mentioned may exist. We can trace the relationship holding between visual consciousness and any factor in any stage, either afferent or efferent, in the total response system. As we become more and more capable of anatomizing and of atomizing this system, we shall more and more lose our interest in the traditional division of problems into sensation, perception and action, and shall concern ourselves first with a complete understanding of the purely physiological mechanism of the response, and second, with an ascertainment of the direct psychophysical laws which associate the visual consciousness with the most central or focal process in the cerebral cortex. In such phenomena as visual hallucinations and illusions, occurring either in normal or abnormal states of the nervous system, we find ourselves forced, even under present conditions, to seek for the essential determinants in the central process.

Section 4.—The Principal Methods of Visual Research.

The Psychological Methods.—In endeavoring to perfect our knowledge of the general system of realities indicated by the above analysis, a considerable variety of methods are available to us. However, unfortunately, the techniques of these methods are at present in the majority of instances so poorly developed that many gaps must for a long time continue to exist in our empirical results, so that we must have recourse to inference and hypothesis in order to piece out the system. Before dealing with the general principles with which our visual theorizing must conform, let us consider briefly the chief empirical methods which are available. These methods can be divided naturally, in correspondence with the classification of essential constituents in the visual problem, into psychological, physiological and psychophysical procedures respectively.

The psychological method of *pure introspection,* as applied to vision, consists simply in a straightforward description of visual experience in its own terms without reference to its physical or physiological conditions. Such a description, however, is not easy to give, since the majority of common-sense conceptions, when applied to vision, prove to have meanings not restricted to what is immediately found in consciousness. The stuff out of which visual experience is made consists almost exclusively of color and depth, but if in common-sense discussion we should say that the book which we see before us is made of color and depth alone, we would seem to speak nonsense. For this reason it is necessary to develop a technical vocabulary for the description of visual consciousness in exclusively psychological terms and to train ourselves in the use of such a vocabulary without implication of factors which lie outside of our immediate visual presentations. We must learn to avoid "the stimulus error."

This type of mistake is constantly being made by the vast majority of workers in the field of psychophysical optics. Colors are confused indiscriminately with wave-lengths and even with retinal reactions; visual percepts are continually being identified with physical objects in the visual response process; and the successions of consciousnesses which make up visual experience are frequently confused with the motor adjustments which they accompany. To apply the psychological method we must strictly avoid these confusions, which are latent in all common-sense thinking, and must insist upon the treatment of visual consciousness as a thing in itself which must be described in its own terms and only later be considered in external relationship to the components of the response system.

In order to carry out a strictly psychological analysis it is necessary to have terms or symbolic means for designating, first, all of the distinctive elements which enter into the constitution of the visual consciousness, and, second, the various ways in which these elements can be combined. The terminology for the elements is provided by the *color solid* and by the notion of the visual depth factor which we shall consider in greater detail below. The color solid, with its attendent nomenclature and symbolism, is exclusively a psychological construction, having no reference whatsoever to any physical or physiological conditions which either conceivably or actually accompany the presence of color in consciousness. It is impossible, however, to describe completely any visual consciousness merely by enumerating its chromatic or stereoscopic constituents. We must also specify the pattern or form of combination of these elements. Although this pattern is spatial in character it is obviously not identical with that of the object, since visual space is non-Euclidean. Moreover, it would not be legitimate to refer the configuration of colors and depth factors to any physical system of axes. The reference system and the disposition of the elements with respect to it must be exclusively subjective in definition or manner of description. Such a scheme is provided by our conception of the *visual field* with its center at the point of clearest vision and its intuitively determined horizontal axis. Within the visual field with reference to its central point and horizontal, we can specify the positions of any point of color by means of a subjective system of polar coördinates which employs just noticeable differences of position as units. Such a scheme deals adequately with the two dimensions of visual consciousness which are occupied by the color factors. The third dimension, which is built up of depth elements, may be referred to the empirical and cyclopean eye as a polar origin from which stream out linear series of just noticeable depth distances which terminate on the two-dimensional color field. It is to be noticed that the components of visual consciousness, thus described, are presumably not indefinitely subdivisible intervals, and are in any concrete case present in a finite number. Space thresholds, whether along or perpendicular to the empirical line of vision, represent ultimate atoms of visual consciousness, and it is the manner of concatenation of these diversified constituents which actually comprises the visual space consciousness. Visual space is not something preëxistent, in which these elements are disposed, but is itself a construction of the elements in question. The problem of the mode of correlation holding between this visual space system and that in which the visual response object, or on the other hand the visual brain process, exists, is as real a one as that of

the relationship which obtains between the color components of visual experience and the characteristics of the stimulus or receptor activities.

PHYSIOLOGICAL METHODS.—The strictly physiological methods of studying vision must be regarded as divorced as completely from all considerations of consciousness as are the strictly psychological methods from all physical or physiological conceptions. The physiological methods constitute an attack upon the physical nature of the response system in and for itself, without reference to its psychical concomitants. These methods may be classified among themselves with reference to the various stages in the response mechanism to which they are adapted. They may appropriately be discussed in the serial order which characterizes these response stages.

The Object.—The first stage in the response, the physical object, is clearly a fact lying outside of the domain of physiology as it is ordinarily defined, and is a topic of general physical science amenable to all of the methods of physics and chemistry. Of course in special cases, which are in everyday life of frequent occurrence, the object of vision is itself a living organism, but the peculiarities which make it such an object are not characterstically biological but reside in its power to reflect and to absorb visible radiation. The physicist tells us that this action occurs mainly in the superficial molecules or atoms of an opaque body, although in transparent objects the influence of all of the molecules which comprise them may be exerted upon the radiation which finally becomes a visual stimulus. The *intrinsic* properties of an opaque body which concern us in the study of vision are limited to its size, its shape, and the reflection characteristics[27] of the surfaces which are presented to the eye. The reflection characteristics may be subdivided into those which determine the directive distribution of the reflected radiation and, second, those which govern the ratio of reflected to incident total intensity for the various wave-lengths of the visible spectrum. Both of these characteristics will presumably vary with the position of a considered point on the surface of the body, a description of the manner of such variation specifying the optical texture of the surface in question. In the case of transparent objects it will ordinarily be necessary to add to a knowledge of their reflection characteristics a determination of their transmissive properties. The latter will involve factors influencing directive distribution (refraction) within the body as well as those which determine the ratios of transmitted to incident intensities for each wave-length of visible radiation. The *extrinsic* properties of the object which are involved in vision include its distance from the eye and its orientation with respect to the line of sight; and among such properties we may

also include for convenience the total intensity, spectral distribution, and direction of the radiant energy which impinges upon each point of the object surface.

Concerning methods for measuring size, distance and pattern arrangements little or nothing needs to be said. It should be noted, however, that for monocular vision the absolute size of an object has no significance apart from its distance from the eye, and that a measure of the angle subtended by the object, or any of its features, at the nodal point of the eye constitutes a complete specification of its spatial magnitude as a monocular visual stimulus. Such a visual angle will in general be a *solid* angle with a definite shape, requiring therefore a complex specification. In binocular vision these angle characteristics must be specified separately for each eye. The reason why the spatial characteristics of the object can be expressed in purely angular terms either in monocular or binocular vision clearly consists in the fact that the *retinal images* are completely deducible from such angular specifications. Binocular vision rests of course, not upon the images alone, but also upon the state of convergence of the eyes, which directly involves the distance. Even monocular vision is not wholly without dependency upon absolute distance, since the latter determines by optical principles the relative definition or sharpness of the retinal images which are formed of objects at different distances from the eye.

Methods of measuring the reflection and transmission characteristics of bodies are of the utmost importance for the study of vision. Lack of knowledge of these methods has been responsible for the unfruitfulness of a vast number of otherwise commendable researches in this field. A specification of reflection or transmission characteristics which will be adequate for all purposes can only be obtained by spectrophotometric or spectroradiometric technique. By this technique the refraction or transmission coefficients are obtained for each wave-length of the visible spectrum and permit a curve to be plotted showing how the reflection or transmission varies as a function of wave-length. From such a curve, or the tabulation of data upon which it is based, it is possible to derive, by selection or integration, specifications of reflection or transmission properties which are appropriate to any possible situation in which the object in question is involved. For example, if the illumination of the object is by monochromatic light we have only to consider the reflection or transmission coefficients which correspond to the wave-length of this given illumination; or if the illumination be not monochromatic but nevertheless be restricted to a limited range in the spectrum, the spectral distribution for reflection or transmission over this given range can be com-

bined with the visibility or with the color excitation functions for the same range to yield an integral evaluation either of the luminosity or chromatic characteristics of the body for the specified wave-length range. It is clearly beyond the scope of the present monograph to describe the methods of spectrophotometry or of spectroradiometry in detail.[28]

In attempting to evaluate a physical body as an object of vision, we must also consider, of course, in addition to its inherent optical properties, the nature of the radiation which impinges upon it from external sources. Some objects, naturally, are their own sources of radiation, and in such cases we must be concerned not only with reflection or transmission, but also with emission characteristics. We must ascertain by spectrophotometric or radiometric methods the intensity of the radiation for each wave-length which is emitted in the direction of the observer's eye, this intensity being measured in ergs per second per square centimeter per steradian (the unit solid angle). In the vast majority of instances, however, objects are seen by reflected or by transmitted radiation. The situation with transmitted or reflected light is not radically different from that which involves direct emission by the visible object, since in either case all that we need to know is the detailed character of the radiation which actually leaves the surface of the body in the direction of the eye. However, it is often convenient to be able to deduce the characteristics of this radiation from a knowledge of the reflection and transmission characteristics of the object, combined with the spectral distribution and other attributes of the radiation which impinges upon it. To accomplish this result we must know the intensity of the incident radiation for each wave-length of the spectrum and the directions of incidence of its component rays. This intensity will be measured in terms of ergs per second per square centimeter, the radiometric analogue of illumination. It will of course be necessary in combining these data with those relating to the object itself, to consider not only the spectral characteristics of the latter but also its shape, position and orientation with respect to the eye of the observer.

The Stimulus.[29]—It will be noted that in the study of vision the object needs to be specified only in so far as it determines the character of the radiation which leaves its surfaces in the direction of the eye. Knowledge of the optical properties of the object is useful merely as a means to the specification of the stimulus. As a matter of fact, as has previously been indicated, a real image possesses all of the properties which are requisite to constitute an object of vision, although such an image has no electronic or atomic structure but consists wholly of

radiant energy or of stimulus stuff. This seeming irrelevancy of the object's properties, provided the nature of the stimulus is known, is not, however, a peculiarity of the initial stage in the visual response, since, if we accept the general psychophysical views which have been propounded above, it would appear that a complete specification of any stage whatsoever in the afferent branch of the response system is adequate in the presence of all of the succeeding stages to determine the nature of our visual experiences. Nevertheless, if we define vision as the total process, it is part of our problem to understand the linkages of all of the successive stages, as well as the manner of association of the central stage with consciousness. Thus the physicist in determining the laws of emission of radiation from sources, of the propagation of such radiation through space and of its absorption, transmission, or reflection by non-emissive bodies, is working out in detail the preliminary stages in the visual process. Just where the problem of the physiologist or the psychophysiologist begins it is of course difficult to state, but it is certainly present in an important degree in the stimulus stage.

The stimulus stage of visual response may be considered to lie between the emitting or reflecting electrons within the object and the absorbing sensitive mechanisms in the retina. It overlaps the object on the one hand and the sense-organ process on the other. This overlap is not only physical and geometrical but also logical. From a purely physical point of view the stimulus to vision can be nothing but radiant energy, characterized by the possession of definite wave-lengths and intensities measured in units of energy, space and time. But we know that very few out of the total gamut of wave-lengths which are sent off by objects, actually excite the retina, and hence only a small portion of all possible types of radiant energy can be defined as visual stimuli. Ordinarily we distinguish between visible and invisible radiation and apply the name "light" to the former. However, it is clear that this distinction does not rest upon any peculiarity of the radiation itself, but merely upon its relationship to the retina, or more strictly speaking, to consciousness. Moreover, we are forced to recognize the fact that the luminous or photometric value of any given sample of radiation varies radically with its wave-length even when the radiation in question is properly classed as "light"; so that it seems necessary to define light in a quantitative manner as being not merely visible radiation, but rather as "radiation in so far as it is visible." This means ultimately that we must determine measures of light first by ascertaining the physical intensity of the given radiation sample, together with its wave-length constitution, and second

must multiply the intensity for each wave-length by a factor known as the visibility of radiation of the specified wave-length, the resulting products being summated to yield an integral light value.[30] All photometric measures are the outcomes of either an explicit or an implicit computation of this sort.

There appears to be considerable room for argument as to whether the properties of the visual stimulus should be expressed in photometric or in radiometric terms. In the latter case the radiant energy impinging upon the cornea would be described wholly without reference to its power to excite the retina. In the very beginning of our studies upon vision we should of course be obliged to consider all physical agencies which could possibly be operative upon the retina, in order to determine what among these agencies were actually responsible for its reactions. In a more advanced phase of our investigation we should have ruled out many of these agencies as being irrelevant and among the latter would be included ultra-violet and infra-red radiation, which fail to excite the retina. Hence, in any case, under present conditions of knowledge the radiation with which we are concerned in our study of vision is limited to a very small range of wave-lengths. If we allow an adequate margin of safety on either side of the visible spectrum and then specify the radiometric analogue of photometric brightness[31] for each constituent wave-length in the direction of the eye and for each point in the object surface we shall have adequately determined the intensity and spectral characteristics of the stimulus. However, it may be argued that an analogous specification directly in terms of photometric brightness is superior, since it measures the *stimulus value* of the radiation, dealing with it as an actual stimulus and not merely as a physical entity. Practical considerations also favor the photometric method as opposed to the radiometric one, on account of the extreme delicacy and complexity of the radiometric technique. In practice both the photometric and the radiometric methods prove useful, a choice between them being determined by the nature of the specific problem which is under consideration.[32] In general, if we are endeavoring to work out a relationship, physiological or psychophysiological, which associates consciousness or any inner stage of the visual response with stages which lie prior to the receptor process, we must specify the stimulus in radiometric terms, since in such a case it is confusing to import into the stimulus, properties which depend upon variables whose connection with it we are seeking to ascertain. For example, a visibility or luminosity curve determination must clearly rest upon a specification of the stimulus in energy units. On the other hand, if our interest in the stimulus arises from a con-

sideration of the relationships obtaining between stages of the response or consciousness, which all lie subsequent to the receptor process, it will probably prove more helpful to express the stimulus in photometric units, since photometric measures represent in this case the degree in which the intensity characteristics of the given sample of radiant energy are actually effective in the remainder of the response activity. For example, in the study of contrast phenomena the expression of stimulus values in radiometric terms would make it very difficult to arrive at any comprehensive generalizations, whereas if they are photometrically expressed it appears that these phenomena are, in certain of their aspects, very simply determined by the luminosity value alone.

If it is decided to formulate the stimulus in photometric or light units,[33] the investigator should consider carefully whether he should base his measures upon the standard visibility curve representing the response of the average normal eye[34] or whether he should employ the visibility curve of each given observer with reference to that observer's results. If a large number of observers are employed and their results are averaged it may be legitimate to make use of standard visibility and photometric conceptions, but in the majority of cases it would seem necessary to have all photometric equations or measurements established by the individual observer whose visual system is under examination, since individual visibility curves vary in an important way. In case such individual stimulus values are employed, the results necessarily lose some significance as specifications of the conditions of experimentation. For this reason if the photometric method is adhered to throughout it may be necessary to utilize both individual and average normal photometric evaluations, the former having reference to the specific psychophysical problems which are under examination while the latter are utilized to permit a reproduction of experimental conditions in some subsequent investigation. Standardized photometric values, determined with reference to the average normal visibility curve, may be regarded as indirect radiometric measures in which a highly selective radiometer, the eye, is employed. Such standardized measures can be reduced to radiometric values by means of the absolute visibility function upon which they rest. The use of tested normal observers,[35] or of data corrected to normality by a knowledge of the degree of departure of the individual eye from the normal, form a convenient means for determining energy values of the stimulus; and such a method, although logically complex, is experimentally simpler and the final results probably more reliable than one based upon direct radiometry.

Judged by the reports of their investigations, the majority of visual

researchers possess a very inadequate conception of the intensity characteristics of the stimulus which are of actual importance in vision. It is very common to find a specification of the illumination of the object expressed in meter-candles or foot-candles, without any reference being made to the reflection characteristics of the object. Even if the total reflection coefficient is specified, the data are still incomplete unless it is known that the object exhibits perfectly diffuse reflection or follows Lambert's law. Assuming that the stimulus is to be described in photometric rather than in radiometric terms, the conception which provides a really adequate determination of its value as a stage in the visual process is that of brightness or of intrinsic brilliancy.[36] This conception is equally applicable to directly emitted, reflected, or transmitted light. Its accurate relevancy to visual problems depends upon the fact that the illumination of the retina in the formation of the retinal image is directly proportional to the photometric brightness of the corresponding object area or point. Photometric brightness, naturally, is a concept which depends for its definition to a large extent upon the state of affairs in the space surrounding the object, since it involves the direction in which the rays leave the object surface, as well as their density. It may be defined as the candle-power per unit area measured from the given point of direction and is proportional to the light emitted per second per square centimeter per unit solid angle in the direction specified. The analogous radiometric expression is naturally obtainable by dividing the photometric brightness measure by the appropriate corresponding absolute visibility value. In practice, the most direct way in which to obtain a satisfactory photometric specification of the stimulus intensity is to make a measurement by means of a brightness photometer upon the object from the actual point at which the eye is situated in the experiment.

The wave-length characteristics of the stimulus may be completely expressed for each point of the object surface by means of a function or curve representing the photometric brightness or its radiometric analogue for each wave-length in the visible spectrum. From such a curve or function one can determine any special characteristic of the stimulus, a knowledge of which is required for special purposes. If this distribution curve is in absolute units of intensity, it provides a basis for a study of the intensity or luminosity characteristics of the response as well as the chromatic aspects of the latter. In special cases it is sufficient to know the integral luminosity value of the stimulus for each presented point of the object and in other cases, where chromatic factors are under consideration, it is sufficient to

know the integral chromatic value of the stimulus expressed in terms of the three-color excitation curves. However, in general, it is advisable to determine the stimulus analytically by means of its spectral intensity distribution, since it is possible to derive all other selective or integral characteristics from this analytical specification.

As previously noted, the size and shape features of the object may be expressed completely for visual purposes in terms of the angle or angles subtended by the features in question, at the nodal point of the eye or eyes. These angular measures may also be regarded as establishing the size and shape characteristics of the *stimulus,* since the angles in question are determined by the direction of pencils of radiant energy which pass through the pupil. The key to a proper understanding of stimulus properties for the purposes of visual investigation is to be found in the retinal image. As previously noted, it is because the size and shape characteristics of this image depend upon angular magnitudes outside of the eye that these magnitudes are of crucial and sufficient significance in visual work. It is for an exactly similar reason that brightness or its radiometric analogue is the important intensity characteristic of the object or stimulus, since it is upon this characteristic that the retinal image illumination or its radiometric analogue depends.[87]

The Sense-Organ Process.—Although vision is counted as a distance-receptive sense, having stimuli lying outside of the organism, the true physiological stimulus lies within the eye in the form of the radiation which impinges upon the retina. The exact characteristics of the retinal image, of course, depend not merely upon those of the stimulus, as the latter exist outside of the eye, but in an absolutely crucial way upon the structure and action of the eye itself. The methods of determining the structure of the eye are those of anatomy, gross or microscopic, although on account of the transparency of the ocular media special methods are applicable to the ocular apparatus which are not available in all other fields of anatomy. The ophthalmoscope, the retinascope, the skiascope and the corneal microscope (supplemented by Gullstrand's slit-lamp) provide us with instruments for examining the tissues of the living eye in a very satisfactory way. The ophthalmometer permits us to determine accurately the curvatures of ocular refracting surfaces. The size of the pupil can readily be observed and measured. Entoptic methods of observation also provide us with means for studying certain structural features of the eye. By means of these and subsidiary procedures we are enabled furthermore to obtain considerable information concerning ocular *functions* by noting the changes which occur in the optic structures. For example, by

means of the phakoscope we can obtain direct evidence of the changes in curvature of the crystalline lens surfaces in the act of accommodation; we can follow the changes in size of the pupil as it adjusts itself to varied intensities of retinal illumination, or in its associated reflex movements which accompany accommodation.[38]

On the whole, however, our knowledge of the sense-organ processes depends upon deduction and inference, and to a considerable extent upon use of the method of hypothesis. Helmholtz was able to work out satisfactorily the main dioptric or refractive functions of the eye from the data of ocular anatomy in combination with the established general principles of physical optics.[39] By means of such principles, in combination with other specific anatomical or histological facts, we can deduce the nature of minor processes such as scattering of light by inhomogeneities of the ocular media. With regard to the results obtained by such relatively rigid courses of reasoning, we may feel very secure, but these methods do not at present suffice to answer all of the questions which we are impelled to ask. For example, Helmholtz's theory of the mechanism of accommodation, involving the release of tension of the suspensory ligament of the lens by the contraction of the ciliary muscle, although a generally accepted account, borders on the line between legitimate inference and mere hypothesis. Naturally, the more actual data we have concerning the structures of the eye, together with their physiological properties, the more we can expand the domain of legitimate deduction, and the easier it will be to subject speculation and hypotheses to the test of rational argument.

The mechanisms of the visual sense-organ offer a complex constellation of afferent and efferent processes, the latter being dictated ultimately by the former, but being also responsible in turn for their regulation. The separation of the afferent and efferent factors in the mechanism may be accomplished by limiting the latter to the changes which are undergone by radiation, or the stimulus, in passing through the ocular media in any given phase of adjustment of the eye; the determination of the given ocular adjustments, together with changes in such adjustments, being regarded as an efferent affair. The afferent sense-organ stage is thus almost exclusively involved with the processes by which the true physiological visual stimulus, the retinal image, is developed from the complex sheaves of radiation which impinge upon the cornea. It is the problem of the efferent sense-organ process to trace these sheaves of radiation through the successive ocular media and to understand exactly what happens to them at each step, so that given any externally incident stimulus it will be possible to deduce accurately the nature of the resulting image

upon the retina. We know that the two most important factors in this process are the refraction of the rays which occurs at the corneal surface, and the regulation of their intensity by the size of the pupil. We are obliged to add, however, not only the supplementary variable refraction which occurs at the lens surfaces and within the lens, but also losses of intensity due to absorption and scattering in the substance of the cornea, the aqueous humor, the lens, the vitreous humor, and the internal layers of the retina itself. Although our knowledge of the main refractive phenomena of the human eye is in a very satisfactory state, much still remains to be done in working out the details of what may be regarded as refractive defects of the normal or of the abnormal eye. In such work it seems most fruitful to combine the methods of anatomy, physical optics and psychophysical observation, and in many researches it has proved possible by bringing to bear these three lines of evidence to arrive at very secure conclusions. As a striking illustration of such a research we may mention Hartridge's monograph[40] on the chromatic aberration of the eye, or that of Ames[41] on achromatic aberrations. In endeavors of this sort a judicious use of the method of hypothesis is practically essential.

It would appear that many controverted questions relating to human vision could be settled if we possessed more statistical information concerning the anatomy of the human eye, such information being obtained by post-mortem dissection made as soon as possible after death. The problem of the yellow spot as a structure present in the living retina, for example, presents itself in this connection. However, the development of methods for examining the structures of the living eye seem to be even more important. Gullstrand's invention of the slit-lamp has extended the usefulness of the corneal microscope so that it promises to yield a rich fruit of data regarding the structures of the living eye.[42] Improvements upon the essential principle of the ophthalmoscope are also being made and it would seem that this principle should be capable of extension to answer many pressing questions concerning properties of the ocular media. Examination of the retina with red-free rays is adding to our knowledge along these lines and it seems probable that the use of monochromatic rays in such work would yield important data, for example, information concerning the spectral absorption of the eye material, the presence or absence of special pigments in various portions of the retina, etc. A well-considered use of mydriatics will often permit the ascertainment of facts concerning the ocular mechanism which might otherwise be inaccessible.

One component of the visual sense-organ process which has failed to receive due attention in the methodology of visual investigation is

the regulative action exerted by the pupillary aperture upon the intensity of the retinal image. If the latter is to be regarded as the true physiological stimulus, a mere specification of the stimulus intensity outside of the eye will not suffice to determine the remainder of the visual response process. The intensity factors in the retinal reaction must clearly depend upon the "photographic speed" of the eye, as well as upon the brightness of the object surfaces which are presented to it. Since the pupil is capable of varying from a diameter of approximately two millimeters to one of eight millimeters its area varies between limits having a ratio of 1 to 16, involving a factor of sixteen hundred per cent. Although the intensity of the external stimulus may vary from a visible magnitude of one to another of ten billion units, a factor of sixteen hundred per cent is nevertheless by no means negligible, especially when we consider that the eye is sensitive to a variation of about one per cent. It is also true, of course, that the average opening of the pupil is a function of the intensity of the external stimulus, but it depends at the same time upon the state of adaptation of the retina, and even under maximally equilibrium conditions it shows marked variations. It therefore seems essential in any accurate work upon visual reactions to specify accurately the size of the pupil, and in order to accomplish this it is advisable not to rely upon the natural pupil, but to employ an artificial pupil,[43] or an aperture placed immediately in front of the cornea, such aperture being smaller than the smallest diameter of the natural pupil under the given conditions of work. If we know the size of the pupil and the brightness of the external stimulus surface we shall be able to determine, at least very approximately, the intensity of the retinal image.

In order to facilitate the specification of the visual stimulus intensity in terms which shall be significant for the retinal image, the writer has suggested the employment of a special intensity unit called the photon.[44] The photon is defined as that intensity of stimulation which accompanies the use of a pupillary area of one square millimeter and an external stimulus surface brightness of one candle per square meter. In order to obtain the photon value of any given stimulus it is only necessary to multiply the brightness values, as specified, by the area of the artificial pupil or natural "entrance pupil" in square millimeters. Various stimulus conditions will then be intercomparable, regardless of the absolute individual magnitudes of the pupillary areas and stimulus surface brightnesses, provided the products of these two factors are known in each case. The photon, obviously, expresses the stimulus on the basis of photometric standards and may be reduced to its radiometric analogue by dividing by the appropriate absolute visibility

value. As it stands, unreduced, it is essentially a measure of retinal illumination.

The Receptor Process.[45]—When we pass from the retinal image to the retinal receptor process we pass truly from a domain of light into one of darkness. It is our profound lack of empirical knowledge of the nature of this process which causes the corresponding stage in the response to be the subject of such a vast amount of theoretical speculation. However, methods of empirical attack upon the problem of the retinal mechanism are not wholly lacking. We must consider, in the first place, the purely histological study of retinal structures upon which any adequate theory of the retinal mechanism must largely be based. It is to be regretted that relatively little work upon the microscopic anatomy of the retina has been done in recent times, the epoch-making researches of Ramon y Cajal having found no recent worthy successors. It is to be hoped that a renewed study of the minute anatomy of the rods and cones, possibly employing microchemical methods, will eventually arise. Applications of the ultramicroscope should also yield useful information. In the case of animal retinas, which may be examined in default of human specimens, modern systems of vital staining might yield valuable results.

The chemical study of the retina, which was initiated by Kuhne[46] in his separation and studies upon the visual purple of the rods, is being continued at the present time by Hecht.[47] The demonstration of this rod pigment and of its properties has greatly assisted our understanding of dark adaptation and of the characteristics of twilight or scotopic vision, and greater refinements of chemical technique may be expected to reveal further illuminating details. It is much to be desired that someone should attack the question of the existence of a *cone* pigment employing methods which are sufficiently delicate. Colorimetric technique is of great utility in researches of this character.

Another method of direct attack upon the retinal mechanism is to be found in measurements of the electrical action and rest currents of the eye. The researches of Fröhlich[48] and of Bovie and Chaffee[49] have shown that it is possible to determine the electrical reactions of even very small sections of the retina. It is not inconceivable that eventually a technique may be developed by which the response of a single rod or cone can be recorded in this manner. The application of the vacuum tube amplifier to the neuro-ocular electric effects by Bovie and Chaffee permits the variations in potential of the tissues to be recorded without necessitating any appreciable flow of electric current, with its accompanying disturbing effects. At the same time all of the changes are greatly magnified but without distortion. The possibilities

which are latent in this technique seem almost unlimited. Such studies, however, are of course confined to the animal retina.

In the case of the human retina the method of psychophysical experimentation probably provides the best available procedure for obtaining relevant information. However, it is necessary to interpret data obtained in this way in a more or less speculative fashion in order to arrive at conclusions regarding the retinal mechanisms. In attempting to apply this method we shall be assisted by an understanding of the exact manner in which our visual experiences depend upon stages in the response outside of the retina. In general, we must endeavor to arrive at criteria by which we can determine whether a given visual effect, introspectively observed, rests primarily upon a retinal, a conductional, or a central activity.

The Afferent Nerve Stimulation and Afferent Conduction Processes. —Available methods of studying the processes occurring in the conducting elements of the retina, the optic nerve, and the optic tract appear to be limited to the measurement of electric action currents and to inferences based upon psychological observations, in combination with established general principles of nerve activity. It is possible in an animal subject to tap off the action currents of the nervous conductors at any point in the afferent conduction chain, or even at the cerebral cortex itself. Relatively little work of this sort has been done with the eye *in situ,* although the majority of studies upon the electric phenomena of the eye have involved the electric properties of the optic nerve stump. By the principle of nerve fiber degeneration we can trace the paths of particular optic nerve fibers from the retina to higher centers. Also by noting the effects of pathological degenerations upon the visual field in a human subject we can correlate various sections of the optic nerve or optic tract, or finally of the visual cortex, with the retinal field.

There is a striking entoptic effect which was first observed by Purkinje and has been called by Mrs. Ladd-Franklin the "blue arc effect" which provides us with psychophysical materials for studying certain aspects at least of the retinal conduction process.[50] This phenomenon consists of a pair of arc-shaped bands of bluish luminescence which can be observed in the visual field when delimited regions in the center of the retina are locally stimulated, preferably by red light. These bands appear to be due to cross stimulation of retinal receptors, or radial conductors, by the nerve currents set up in the tangential nerve fibers of the retina which connect locally stimulated regions with the optic disk. Studies made by the writer[51] upon this phenomenon indicate quite clearly that the retinal nerve currents

obey the all-or-none principle, which has been found to apply to other nerve impulses, and it is to be expected that a careful analysis of all the conditions surrounding this blue arc effect will provide us with very considerable data upon which to argue concerning the nature of the afferent conduction process in vision.

The Central Processes.—The central processes may be studied in animals by means of action current effects, using for example the vacuum tube apparatus which has been devised by Bovie and Chaffee. Work of this sort is being carried out by MacPherson and others. In the human subject, psychophysical methods appear to be the only ones which are at present available. As a rule these involve a comparison of the defects which are present in the visual field in pathological cases, with the lesions which coexist with them in the brain centers. The conditions of warfare provide us with a rich assortment of specimens for studies of this sort, and much has been learned regarding central functions of vision as a result of the recent conflict in Europe.[52] In rare instances it is possible to stimulate the cortex of a living human subject electrically and to obtain introspections reporting the results in consciousness. It is also possible to carry out similar experiments upon animals and to argue as to the modifications of experience which are involved, by noting the nature of the accompanying motor adjustments, for example the resulting movements of the eyes. The analysis of the central processes by psychophysical methods is not restricted to a mere topographic study of the interrelations of the visual field and the cortical projection areas, but may involve a determination of individual mechanisms in the centers which are responsible for various general attributes of visual consciousness, such as color, solidity, localization, etc.[53]

The Efferent Conduction, End-Plate, and Effector Processes.—The efferent processes which are related to vision may be divided into those which are essentially ocular in significance and those which involve the general musculature of the body. The latter are obviously open to the general methods of investigation which are applicable to all organic behavior. It is quite likely that innervations of the skeletal muscles which are controlled by vision, possess characteristics which are dependent upon the receptor processes upon which they are based, so that the science of visual response cannot be regarded as complete, even when it has considered exhaustively the efferent ocular processes, as well as the afferent and central activities which are related with the optic nerve impulses. However, it lies outside of the scope of the present monograph to consider in detail these more general relationships of vision.

The visual sense-organ is unique in the complexity of its special motor adjustments, three of the twelve cranial nerves being concerned with ocular regulation. The principal muscular systems of the eye itself are the ciliary muscle which controls accommodation, the muscles of the pupil, the external muscles of the eyeball, and the muscles of the eyelid. In endeavoring to trace out the efferent conduction paths and the subcortical motor nuclei of the corresponding nerves, Nissl's method of noting the central lesions which occur after extirpation of the muscles has proved very useful. Another method, operating in the reverse direction, consists in restricted electrical stimulation of different portions of the central nuclei, with observation of the accompanying muscular contractions. Natural and artificial lesions in limited portions of the efferent nerve apparatus also permit inferences as to the paths followed by the oculomotor impulses. All of the well-known methods of tracing paths of nervous conduction are applicable to these problems. In studies upon oculomotor, as well as upon other specific forms of response, it is necessary to consider independently lines of response which operate separately, or sometimes together, through a number of different nerve centers arranged in a hierarchy. Movements of the eyes, for example, may occur wholly without the intermediation of cortical activities or on the other hand they may be regulated absolutely by cortical influences. The distinction between reflex and voluntary movements, however, is not a categorical one, since both the higher and the lower centers may coöperate in controlling a single ocular adjustment, which could not be carried out by either of them alone. Although it is possible for us to work out in animals, and to some extent in man, the paths by which the oculomotor impulses are transmitted from the centers to the ocular effectors, we seem at present to be lacking any definite method for ascertaining the mechanisms by which these ocular efferent currents are released and graduated in the delicate manner required to yield the precision of movement which the eyes exhibit.

For the direct study of the ocular effector processes, many elaborate and ingenious techniques have been developed. Among these we have already mentioned the phakoscope of Helmholtz for observing the accommodative movements of the crystalline lens. A number of devices for determining pupillary apertures and changes in aperture have been invented, for example, the wedge employed by Nutting. For the accurate recording of pupillary changes the motion picture camera furnishes a satisfactory means as applied for example by Reeves.[54] It is also possible to record pupillary movements photographically, by forming an image of the pupil upon a uniformly mov-

ing, sensitive film. Another system for determining pupillary apertures where direct observation of the pupil is difficult, is by means of a photometric equation between two stimuli one of which is controlled in intensity by the pupillary area while the other depends upon rays which pass through the pupil in a concentrated cone without being intercepted by the iris in any position. For the observation and recording, photographically, of ocular movements the corneal reflection has proved very useful. Very ingenious methods have been devised by Dodge and others for recording eye movements under the closed lid, making use of the variation in contour of the lids as the bulging cornea moves underneath them.[55] Dodge has also invented an optical compensation apparatus [56] which permits movements of the eyes to be recorded independently of simultaneously occurring displacements of the head, the latter also being registered independently.

THE PSYCHOPHYSICAL METHODS.—The psychophysical methods of studying vision are naturally the only ones which can permit us to determine the relationships which obtain between visual consciousness and response. The usefulness of these methods, however, appears not to be restricted to this very essential function but is apparent also in connection with certain purely physiological problems. Presumably the entire visual consciousness can be regarded as some sort of symbolic representation of the central physiological stage in the response, and hence its characteristics may be looked upon as specific indices of those of the cortical activity. However, inferences from psychophysical observations are not limited to a bearing upon the central processes but can be extended to any of the afferent stages of the response, since the cortical activity, and hence consciousness, are to a large extent determined by prior afferent activities. Such physiological applications of psychophysical data necessarily involve, of course, deductive, inferential, or hypothetical reasoning.

Psychophysical methods in vision naturally require a combination in a single experiment of psychological and physiological or physical procedures, the outcome of the experiment being to establish a correlation between psychological and physiological variables. The physiological factors which are concerned may belong to any conceivable stage of the visual response, although in the vast majority of cases they are characteristic of the *stimulus*. The study of *visual sensation* is psychophysiological in its methods and is concerned with the relationship between consciousness and the stimulus, sense-organ and receptor processes. *Visual perception* in turn involves the relation between visual consiousness and the object of vision. Since the consciousness in its entirety depends directly upon the cerebral process we

should not expect the correlations which are discovered between consciousness and more peripheral stages in the response to be inviolable. They are not, in fact, purely psychophysical but involve merely physiological links. In practice, we find ourselves mainly restricted to the investigation of such indirect relationships. The general schema of a psychophysical experiment [57] involves two individuals called the observer and the experimenter, respectively. The former is required merely to describe his experiences exactly as they are given to him, this process of description being known technically as introspection. The experimenter, in turn, determines the conditions under which the observer's experiences occur. The experimenter is permitted not only to describe his own experiences but to interpret them physically or physiologically. As a rule the experimenter has devised the technique of his experiment in such a manner as to enable him to express the conditions of observation in accurate physical terms. He is thus able, by combining his measurements and computations with the introspective report made by his observer, to arrive at a formula which expresses a correlation between the observer's experience and the physical and physiological conditions which accompany it. It is, of course, possible for a single individual to carry out such an experiment upon himself, in which case this single individual must at one time formulate a purely introspective account of his experiences and at some different time must ascertain the physical situation which accompanied his reported experiences. The psychophysical experiment thus involves on the part of its participants two contrasted attitudes, the one being that of a direct account of the nature of consciousness as given, while the other is that of an inferential or deductive determination of its physical conditions. In order to attain success in such forms of investigation it is very important that these two attitudes be strictly maintained. Failure of the observer to confine himself to a direct account of his experiences, involving an attempt to specify their physical conditions, is known as "the stimulus error."

Qualitative methods in psychophysiology involve on the part of the observer merely an ability to name the components of his experience in the various orders in which they actually occur. In order to do this he requires simply a sufficiently rich vocabulary of psychological terms, and the power of recognition. However, naïve and even sophisticated observers are frequently lacking in an adequate vocabulary for this purpose, and often their powers of recognition are not equal to the task which is set for them. Thus, in the study of color vision we find that no adequate nomenclature exists for the specification of all possible colors, and very few individuals are able to name colors accu-

rately. For these reasons and also in order to simplify the formulation of results, recourse is had to the *quantitative* methods of psychophysics which are based upon the notion of the "threshold difference."

Whenever the qualitative differentiæ of experience are capable of continuous variation or of being arranged into a continuous series, they can in a sense be *measured* by applying the concept of the just noticeable difference.[58] If we arrange a series of qualities, such as the grays ranging from black to white, so that each member of the series is just noticeably different from each of its neighbors, we find it possible to specify each member in the series by a specific number, and this number may be said to represent the degree of difference which separates the member in question from an initial or rather a zero member, the latter furnishing the normal reference point of the series. There has been a great deal of controversy in psychology as to whether just noticeable differences are equal in all parts of such a scale, but practically it appears that there is no better method of defining equality than in terms of the just noticeable difference. At any rate it is only essential for the purposes of psychophysics that the position of a quality in the series should be adequately determined by its number, the significance of the number being restricted in this case to a purely ordinal interpretation.

It is clear that the establishment of a psychological series, with numerically designated members, permits the experimental determination of quantitative functions having on the one side of the equation a purely psychological variable, and on the other side a physical or physiological variable. Thus we can ascertain brilliance (degree of resemblance to white or degree of difference from black) as a function of physical intensity, or we can correlate hue quantitatively with wavelength. In such measurements we determine the specific physical or physiological conditions for each of the members in the psychological series, and the differences between the physical conditions for adjacent members in the series constitutes the respective physical or physiological thresholds. We may hope ultimately not only to ascertain the forms of the psychophysical functions which connect the attributes of visual consciousness with those of the stimulus but also with the characteristics of other more central stages in the response.

Another type of quantitative psychophysical procedure which is of the greatest utility in psychophysical investigations, involves not the establishment of a just noticeable difference, but of an *equation* in consciousness. Such an equation may involve a complete similarity of the psychological qualities which are being compared or on the other hand it may involve similarity only with respect to a single

attribute, as *e. g.* in the comparison of colors an equation of brightness in the presence of hue difference. Equations of qualities in respect of all of their attributes are often possible even when the physical or physiological conditions of such equations are quite discrepant. This is because there are frequently many different physiological conditions for a single type of consciousness. For example, the color gray or white can be produced by an indefinitely large number of different combinations of complementary spectral stimuli. It is by means of this method of psychophysical equations that there have been built up such functions as the three-color excitation curves or the visibility curve for the spectrum, the former depending upon complete equations whereas the latter rests upon an equation in respect of brilliance only.

Still other methods of achieving quantitative results in psychophysical investigations are possible. The absolute threshold for certain psychological phenomena may be employed under varying physiological conditions to determine a quantitative relationship. For example, an ascertainment of the stimulus conditions which are just adequate to produce a noticeable flicker, in experiments upon intermittent stimulation, suffices to generate quantitative psychophysical laws. Even so vaguely defined an experience as "glare" may function in a similar capacity.

SECTION 5.—THE UTILITY AND REQUIREMENTS OF THEORIES IN VISUAL RESEARCH.

The domain of visual science is one in which theories and hypotheses have been produced galore, and it is a domain in which theories are needed. This need rests upon the fact, which has been made evident by the foregoing discussion of methods, that the whole of the psychophysical response system is at present not open to the methods of direct experimental observation. The cerebral process, with which visual consciousness is most immediately correlated, is practically unavailable for physiological observation and even the stimulus and sense-organ stages in the response are not so immediately accessible as to render the use of hypothesis quite unnecessary. The retinal and afferent conduction processes are almost wholly hidden from us, and the exact character of the direct psychophysical relationship is also at present unamenable to experimental investigation.

On the other hand, the *facts* of vision are at the present time very impressive in their number and extremely perplexing in their complexity. They do not readily fall together into a simple deductive system. Now, a theory or hypothesis of vision is simply an attempt to fill in the gaps of our knowledge concerning the actual mechanisms

which are operative in the visual response system, or of the functions which connect this system with consciousness, in such a way as to unify or "explain" the vast mass of facts and principles which have been established experimentally.[59] A theory of color vision, for instance, must be regarded as an attempt to guess at the nature of the retinal, afferent conductional, or cerebral stages in the response, including a statement of the relation existing between one or more of these mechanisms and the colors themselves, which latter are to be found only in the visual consciousness. If a theory is true, it is at least potentially verifiable by the methods of direct observation. The actual mechanism would necessarily fit in coherently with all of the facts in the case, and consequently a true hypothesis must adequately explain the known facts.

It is clear that consistency with the established facts is an absolutely inevitable requirement made upon every scientific hypothesis, and there are certain very general facts with regard to our present knowledge of vision with which every visual theory must conform. The failure of classical visual theories to conform to these general facts is responsible for their failure in more particular respects. The first of these facts consists in the at present very scattered and obviously incomplete nature of the actual data which are at our command. In the light of this characteristic of our knowledge, all visual hypotheses must necessarily be regarded as tentative in nature. There is at present a vanishingly small probability that anyone can accurately guess the actual nature of the psychophysical mechanism in vision. All useful guesses will necessarily be only rough approximations to the truth, and must be considered subject to modification "without notice" at any time. In spite of this obvious necessity for caution, visual theorists have almost uniformly laid down their doctrines as if they were the utterances of a prophet, and have spent the remainder of their individual lives endeavoring to interpret the facts so that they would harmonize with the implications of their theories. In no case have these efforts to save a theory based upon inadequate data proved successful or useful. It is highly desirable that hypotheses should be couched in as definite a form as possible, but rather for the purpose of rendering them easy of test and possible refutation than to endow them with scientific dignity. The process of visual theorizing will properly be regarded as a highly experimental undertaking in which each hypothesis is looked upon as merely a single step, and possibly an erroneous one, in a protracted theoretical investigation.

Another general respect in which visual hypotheses must conform to the facts lies in the complexity of structure which apparently must be

considered to characterize both of them. In some departments of science, as for example in mechanics, seemingly complex effects may be explained in terms of very simple fundamental relationships. In the light of our present knowledge of physiological mechanisms, however, it seems very improbable that the complex nature of visual phenomena will ever succumb to the explanatory efforts of a simple visual hypothesis. Physiological and psychological phenomena are often even redundant in their causation, similar effects being attributable in different instances to quite disparate causes. The phenomenon of contrast, for example, in vision may depend both upon retinal and central processes.

Visual hypotheses are in the main concerned with the obscure stages in the response which lie between the stimulus and consciousness. Now, although the details of these stages are obscure, it is perfectly clear that each stage must have its own characteristic mechanism, and there seems to be no *a priori* reason why these several mechanisms should be fundamentally similar to one another. Consequently any visual hypothesis, in order to conform to established general facts, must consider independently the supposed mechanisms of the successive afferent to central response stages, or else must confine itself to a specific individual stage. The majority of visual theories have failed to comply with this requirement and consequently cannot be expected to give a satisfactory account of the visual apparatus or to explain all of the facts. The majority of such hypotheses have, at least implicitly, been concerned with the receptor process, although the doctrines in question have frequently been stated as if they applied to the entire afferent response mechanism. However, a considerable number of hypotheses have been advanced which deal separately with different stages or "zones" of the response. Among such "zone theories" may be counted the hypothesis of Donders [60] and the recent speculations of Schjelderup.[61] Donders distinguished only two stages, those of the retina and of the brain, respectively, while Schjelderup designates three, inserting a conductional process between the retina and the brain. It may be doubted, however, whether even three zones are sufficient, as the retina itself contains at least this number of successive neural elements while the cortex certainly embraces many more than this. Surely the visual theorist should envisage the actual serial complexity of visual response while he is attempting to get at its mechanism. Only in this way can he vividly realize the nature of the problem upon which he is working.[62]

A respectable theory of vision must not only specify the mechanisms which are supposed to be operative in each successive stage of the

response, but it must formulate the relations which obtain between the various components of such successive stages. Furthermore, it must state how the central stage, or the stage or stages which are conceived to determine consciousness, are supposed to be correlated with the various attributes of visual experience. The failure of a theory to state precisely the relationship which is supposed to obtain between consciousness and the response mechanism necessarily renders the theory incomplete, although it may not impugn its validity as an account of purely physiological factors.

If visual hypotheses are formulated in accordance with the requirements above suggested it is highly probable that they will prove to be truly useful instruments of research. They will not only tend to link together the various scattered facts of the science, but will suggest new lines of investigation and the possibility of new phenomena which may later be realized under appropriate experimental conditions. New lines of thought will thus be opened up, and if the theories are maintained in a flexible condition, the pursuit of these new ideas may lead us eventually to a coherent notion of the entire visual apparatus and its relationship to consciousness. To attain this ultimate theoretical goal we must have both clearer, and more unprejudiced, theorizing and a more accurate and comprehensive collection of data which are relevant to the theoretical problems.

Chapter III.

PROBLEMS IN THE ANALYSIS OF VISUAL EXPERIENCE

The function of the remainder of this monograph is to review rapidly various aspects of our knowledge of vision. The purpose of this review, however, will not be primarily to summarize the established facts, but rather to indicate the apparently most fruitful lines of future investigation. In other words the facts will be sketched only so far as is necessary to reveal the lacunæ which exist between them. In the ensuing presentation the writer lays no claim to complete accuracy or comprehensiveness, and has naturally been able to suggest the needs for visual research only as they appear from his own point of view. In the present chapter we shall consider certain purely psychological problems, relating to modes of describing visual experience. The next following chapter will deal with the physiological problems of the visual response system, considered by itself, while the final chapter will consider various psychophysical correlations.

Section 6.—The Nomenclature and System of Colors.

Since the problem of introspective psychology is simply that of the description of experience, exactly as it is given, one of its principal tasks is the establishment of a satisfactory system of nomenclature, or a notation for the designation of experiential elements, structures or processes. As has previously been indicated, the two fundamental components of the visual consciousness are color and visual depth, these being arranged in such a way as to constitute the visual field.

The recent report of the colorimetry committee of the Optical Society of America [63] recommends that the word "color" be employed to designate not only visual qualities possessing the attributes of hue and saturation, but also the grays, including black and white. Colors in this sense comprise all possible constituents of monocular two-dimensional visual consciousness. Colors possess three general attributes known as *brilliance, hue* and *saturation,* respectively. These attributes are not to be regarded as elements or components of colors but rather as indications of their relations of similarity or difference. Moreover, the attributes are defined wholly in a subjective manner, without reference to the roughly corresponding physical notions of intensity, wave-length and purity, respectively.

The definition of the three attributes of color is best effected by means of the psychological color solid [64] which consists of a conceptual arrangement of all possible colors in order of their degrees of resemblance or difference. As this solid is ordinarily constructed, it

possesses an axis comprising the linear series of grays or achromatic colors ranging from black to white, while around this axis circumferentially are placed at various angles the different hues, varying degrees of saturation in each hue being represented by distances from the axis. The members of this color solid are conceived to be just noticeably different from their immediate neighbors, in all three dimensions of the solid.

Although the color solid is quite elaborately discussed by psychologists and colorimetricians, its characteristics have been worked out only very incompletely, and a fertile field for investigation therefore exists in connection with it. There must be considered in the first place the problem of the number of just noticeable differences between black and white. Various figures have been assigned by Külpe, König and others on the basis of Weber's law determinations, but it is to be noted that in such determinations changing adaptation plays a very large part, and such adaptation tends to compensate for alterations in the stimulus intensities. The actual number of psychological steps is therefore probably much smaller than the six to eight hundred which is usually assigned. The numbers of saturation steps from various grays to spectral colors of the same brilliance have not as yet been determined. Since the spectral colors are not of equal saturation and have no unique psychological significance, it would seem desirable to determine the number of just noticeable hue differences around the hue cycle for all possible loci of equal saturations. No attempt whatsoever has been made to ascertain these values. The general problem obviously arises in connection with such measurements as to whether the space of the color solid is Euclidean, and *a priori* it seems very improbable that such is the case. A further question regarding the color solid is concerned with its boundaries. From a purely psychological point of view these boundaries may be regarded as indeterminate, but physiological conditions undoubtedly exist which definitely limit them, and such limitations define the possible scope of color experiences. The color solid has been variously represented as a sphere, a cylinder, a double cone and a double pyramid, but sufficient empirical data does not exist at the present time to settle this question.

A further problem relating to the systematization of colors is that of the so-called *psychological primaries* which are usually held to be red, yellow, green, blue, black and white.[65] Although we seem to be able to pick out these four qualities as being unique in character, it is difficult to define exactly the nature of this uniqueness. Mrs. Ladd-Franklin calls them "unitary colors," regarding all other colors, such as orange, purple, gray, etc., as fusions. Titchener speaks of the

psychologically primary hues as being "turning points" in the circumferential boundary of the color solid, but it is obvious that the general system of the solid does not lend itself to this notion. Some writers, such as von Kries,[66] deny the significance of the choice of these six primaries. To the present writer the psychological primaries appear to be individual colors bearing relations of similarity or difference to other colors such that the mode of variation of quality in the color solid undergoes a critical change in passing through them. For this reason he would call them "critical" colors. This question of psychological primaries is one which deserves careful reconsideration in the light of the most modern theories of consciousness and introspective method.

SECTION 7.—THE VISUAL FIELD AND VISUAL SPACE.

Visual consciousness consists mainly in a spatial arrangement of colors and depth elements. It is quite possible, however, that other minor constituents of the spatial pattern can be identified, for example, the "glass sensation" recently signalized by Schumann.[67] It is quite certain at any rate that the exact qualities of colors, considered as psychological elements, vary in relation to spatial or perceptual structures in dimensions or in respect to attributes which are not represented on the color solid. Consider, for example, the distinction between area colors (*Flächenfarben*), surface colors (*Ueberflächenfarben*) and space colors (*Raumfarben*) which has been made by Katz[68] and his followers. The phenomenon of luster, which appears in binocular vision under certain circumstances, is also in this class.

Visual space can be treated, in and for itself without reference to its physical or physiological conditions, as a quasi-geometrical structure having definite characteristics which may be represented mathematically by the same general methods as are applied to physical or other conceptual forms of space. Visual space is a perspective or image space, characterized by construction with respect to the point of view of the empirical eye. At least by conception, the problem of the form taken by introspective visual space is independent of that of stereoscopic vision, the latter being a psychophysiological problem. Beginnings toward the analysis of visual space have been made by Witte,[69] Giepel [70] and others, but their inquiries require criticism and amplification by further original work. In general, as previously indicated, it appears that binocular visual space can be regarded as a three-dimensional structure of depth elements, arranged radially with respect to the empirical eye and terminating on color elements which enter into the constitution of color surfaces which are, in general, the boundaries of the given finite space mosaic. The question must

be carefully considered whether it is possible to describe the visual consciousness, and hence visual space, wholly in structural and static terms or whether it is necessary to introduce process or dynamic factors. Does the "point of view" which seems to be incorporated in visual space actually reside in its structure or does this point of view depend upon the relation of visual consciousness to other psychical factors such as the thought process?

When we come to consider the physiological bases of visual space we find that the color surfaces which it embraces are determined quite completely with reference to monocular response, while the depth factors—including the disposition of the color surfaces with respect to the latter—are correlated with binocular and other more complicated physiological relationships. It thus becomes possible to discriminate even introspectively between the monocular visual field and the binocular field. The former consists of a two-dimensional system of colors, containing no depth elements, and produced by "projecting" all of the color surfaces in the binocular field upon a single plane, all of the points in which lie at a uniform depth. It is possible, by an act of attention at least, to image such a projection in actual consciousness, and in pathological cases this monocular field may be realized with perceptual vividness. The analysis of visual space at large is favored by an abstraction of the monocular or two-dimensional field from the binocular or depth factors. Roughly speaking, the cyclopean, monocular, field has a circular form, fading off gradually into non-existence at the edges. It possesses a natural, central, reference point which we call the center of vision and also a natural, introspectively discernable, horizontal axis. By the use of these two reference elements it is possible to specify any particular mosaic of colors in the field by applying the method of polar coördinates. The unit of measurement in conjunction with such a scheme would obviously be the just noticeable difference in position in the field at any point. The monocular visual field is to be conceived as a two-dimensional order of finite color elements; these threshold color constituents being thought of, not as lying in a preexistent space, but as *forming* such a space by the manner of their concatenation. Although the elements themselves are finite in magnitude, they have no internal spatial structure. This notion is quite consistent with modern mathematical or logical conceptions of the nature of space.[71]

The depth factors which combine with the color constituents of the visual consciousness as a whole can be treated by means of a three-dimensional polar coördinate system, referred to an axis connecting the empirical eye with the center of vision. The angular units of

measurement in this system will correspond with the threshold units of the monocular field, while the linear units which are employed for measurement along the depth lines will be just noticeable differences in depth position at respective depth locations. In general, visual space as a whole, including the binocular and experience factors, comprises a roughly hemispherical figure, with its center at the empirical eye. The exact contour of the figure, of course, varies radically between separate moments of visual consciousness, the description of the space as hemispherical, having reference primarily only to its angular characteristics.

As previously indicated, the patterns of colors and depth elements which appear in particular cases of visual consequences, are subject to qualitative modifications which may not be expressible in terms of either color or depth. Among these are the modifications which produce definite visual objects or percepts. Visual objects (as distinguished from "objects of vision," which are purely physical) are circumscribed concatenations of color and depth elements which possess a special internal unity or coherence. A complete understanding of the significance of this unification of visual elements will probably involve a study of the relations of vision to other constituents of consciousness, such as thought or language factors and the kinaesthetic or motor sensations. However, it may be noted that the color and depth factors in any visual complex may themselves be radically affected by the integration of the members in this complex to form a percept. In order to detect and to measure such perceptual influences upon color or depth factors, however, it is generally necessary to consider the whole phenomenon in relation to its physiological conditions. The study of "memory colors" (Gedächtnisfarben)[72] is concerned with phenomena and relationships of this sort.

Another problem which is closely related to the above is that of the inherent nature and relationships of visual images. The fundamental constituents of visual images are apparently the same as those of visual percepts, and under certain conditions it is impossible to distinguish introspectively between the two. The formal distinction between them must rest upon a demonstration of the presence or absence of an object, or at least of a stimulus, in the corresponding response process, images being conceived to depend exclusively upon central activities. However, ordinarily there is a difference in "intensity" between an image and the corresponding percept or sensory mosaic. Intensity, as thus conceived, must not be identified with brilliance, but must be regarded as an independently variable attribute of components in visual experience. The difference between visual consciousness of any sort and the physical condition of complete blindness

may be conceived in terms of intensity, but clearly cannot be described in terms of brilliance, since the blind man does not see black any more than he sees white. The fading off of the visual field in its periphery to "non-existence" may also be described as a diminution in intensity, and the vision of objects behind the head is of extremely low or of zero intensity. The question has been discussed, for example, by Jasper and by Grünbaum,[73] as to whether the spaces of visual imagination and perception are co-penetrative, and the answer appears to be affirmative. The study of the visual image will clearly involve a consideration of its relation, on the one hand, to perception and to non-perceptual sensations, and on the other hand, to after-images, positive and negative.

Another very important group of purely subjective phenomena is that of visually perceived motions. Although physically motion is always relative and is motion of a body or particle, in visual experience motion appears to be absolute and may exist even apart from definite displacements of components in the visual field. There is a radical difference, introspectively, between the displacement of the entire visual field with respect to stationary components within it, which accompanies motion of the eyes, and motion of the components within the field while the latter is perceived as stationary. Although, ordinarily, visual motion depends upon the displacement of a continuous visual quality or a component percept with respect to the remainder of the field, experiences are possible in which motion exists without detectible displacement. This occurs, for example, in the phenomenon known as the "movement after-image" and in the "phi phenomenon" which has been studied by Wertheimer[74] and by Dimmick.[75] Although the work of Wertheimer and his follows has greatly increased our knowledge of visual motion perception, a great deal remains to be done in this very important domain.

In general, it may be noted that the problem of describing the visual consciousness in and for itself has been obscured by the study of its psychophysical correlations, which have seemed more amenable to scientific methods. It is highly desirable that clear accounts, based upon a definite nomenclature, should be developed for the various characteristics of the visual consciousness *per se*. It should not be denied, however, that the psycho-physiological experiment provides the best means for arriving at these desiderata, if such experiments are carried out with a clear view of their significance. Obscurantistic conceptions of consciousness, as being simple and unextended, have contributed to our ignorance of visual experience and such conceptions should be resolutely swept aside.

CHAPTER IV.

PROBLEMS CONCERNING THE MECHANISM OF VISUAL RESPONSE (STAGES ONE AND TWO)

SECTION 8.—VISUAL OBJECTS AND STIMULI.

Turning now from the psychological to the physiological and physical factors in vision, we may review briefly the salient problems which relate to the successive stages of visual response, considering these stages in their natural order. We must bear clearly in mind that this response mechanism is to be conceived wholly in physical terms, at no point involving any psychological factors whatsoever.

Visual Objects.—The first stage in the visual response, as we have schematized it, is the object. Although the study of visual objects belongs to a non-physiological section of physics, this study is of equal importance for our general science of vision with the more physiological investigations. However, the relatively much greater progress which has been made in our knowledge of visual objects warrants a very abbreviated consideration of this topic on the present monograph. It may be pointed out, however, that much remains to be done in determining accurately the properties of characteristic physical objects or materials which are of importance for vision. The need of continued research upon the optical properties of bodies is recognized as a part of the efforts which are being made to increase our knowledge and methods of work in general physics. These optical problems are being considered with particular attention by the various committees on Nomenclature and Standards of the Optical Society of America, and reference should be had to the published and forthcoming reports of these committees for summaries of knowledge and outstanding problems in these fields of investigation.[76] The following topics which are being considered by respective Optical Society Sub-committees may be regarded as dealing with properties of the visual object which are of importance for the student of visual response: Spectrophotometry, spectroradiometry, pyrometry, photometry and illumination, reflectometry, refractometry, colorimetry, lenses and optical instruments, projection, and wave-lengths. Some of these topics, such as colorimetry and photometry, involve a combination of object properties with characteristics of later stages in the visual response.

The nomenclature and standards of photometric science have been very thoroughly considered by the Standards Committees of the American Illuminating Engineering Society and also the American

Institute of Electrical Engineers. The work of these societies is being coördinated and sanctioned by the American Engineering Standards Committee. In this field very satisfactory progress is being made, and a substantial order is appearing out of the chaos of concepts, methods, and instruments which previously existed. All of this photometric work, of course, involves the visibility characteristics of the eye itself; but when this aspect of the matter is abstracted, the conceptions and principles—being reduced to radiometric terms—may be regarded as strictly physical and relating to the intensity characteristics of the radiation which impinges upon or leaves the surface of the object.

In the domains of pyrometry, spectrophotometry and spectroradiometry, much remains to be done in determining the spectral distributions of energy, transmission, absorption, reflection, etc., of the various common sources of "light" or of the common substances which transmit or reflect it to our eyes. Very excellent data are available regarding the spectral energy distributions of radiation from vacuum tungsten lamp filaments operated at various efficiencies.[77] Less is known definitely regarding other common sources, including not only the older types of illuminants, but the gas-filled tungsten lamps and the newer types of impregnated carbon arcs. Constant progress is being made upon these problems at the research laboratories of the principal American electric lamp manufacturers, and reference should be had to the publications from these laboratories for much valuable data.[78] With regard to the spectral characteristics of transmitting or reflecting substances a good deal of practically important data has been assembled by Uhler and Wood,[79] by Mees,[80] by Luckiesh [81] and by various workers at the American Bureau of Standards, but there is a great deal of room left in this field for useful work to be carried out by any investigator who has the patience and technique to attack it.

The study of the reflection characteristics of objects is in a much less developed state than that of their transmission properties. The spectral reflection characteristics of a number of standard pigment schemes, such as those of Munsell and of Ostwald, have been determined with sufficient accuracy,[82] [83] but much remains to be done in the study of natural reflection colors such as flesh tints, vegetation, etc. In such studies the determination of the ranges of variability of types of colors is as important as the establishment of averages. The quantitative analysis, as regards intensity alone, of various types of semi-diffuse reflection also offers a relatively uncultivated field of research. Reference may be made to the recent work of

Jones[84] on the gloss characteristics of photographic papers for an illustration of a fruitful line of attack upon this problem.

From the visual investigator's point of view, one of the most important aspects of the physicist's work upon the optical properties of objects lies in his establishment of available standards and instruments. Among important already available assets of this sort must be reckoned the Wratten series of filters, manufactured by the Eastman Kodak Company, the Foot-Candle Meter, produced by the General Electric Company, and the Illuminometer recently put out by the Holophane Company. The first permits the visual investigator to select definitely determined ranges of spectral stimuli to be employed in his experiments. The second will enable him to determine readily the illumination level at which he is working, while the third enables him to measure conveniently the actual photometric brightness of stimulus surfaces. It is to be hoped that further developments of this sort will appear and that a knowledge of them will become common among students of the visual process.

Lenses, prisms, and optical instruments involving them, must be considered as objects of vision, or at least as factors in the production of such objects under many experimental conditions. Workers on vision, in general, need to know more about optical apparatus, and new discussions of such apparatus are valuable contributions to progress in visual science. One of the best comprehensive but simple books on this subject is Edser's "Light for Students."

The Visual Stimulus.—Concerning the second stage in the visual response, the stimulus or radiant energy of certain wave-lengths, very little needs to be said in the present monograph since the systematic study of this entity and its relations to objects is being pursued very energetically and systematically by modern physicists. It may be pointed out, however, that the appearance of the quantum theory of radiation has created a number of dilemmas, the outcomes of which will not be irrelevant to the special science of vision. Already, as previously noted, John Joly has propounded a theory of the receptor process which is specifically based upon the quantum conception. Computation makes it evident that the human retina is sensitive to quantities of radiant energy closely approximating a single quantum for certain wave-lengths. The mechanism of the absorption of single quanta is therefore highly relevant to that of the visual receptor. Moreover, it is conceivable that a study of vision might yield results bearing upon the validity of the quantum conception itself. For example, if it could be shown that vision occurred with total amounts of energy less than a single quantum the quan-

tum hypothesis would seem to be contradicted. We should also expect to find fluctuations in brilliance with vision at very low intensities resulting from the statistical incidence of the quantum stream upon the receptor cell. The student of psychophysiological optics should, therefore, keep closely in touch with modern developments of the theory of radiation.

In this connection may be mentioned the importance to the visual researcher of instruments and methods of computation for ascertaining the absolute energy measures of his visual stimuli. Although he usually finds it most convenient to make his measurements in photometric terms, the systematic importance of determinations in terms of energy cannot be denied. Much remains to be done by the practical physicist in perfecting radiometric instruments such as the radiomicrometer, the bolometer and the radiocalorimeter, so that they can be utilized readily in visual research.

Spectroscopic and spectrometric apparatus for the determination of wave-lengths or frequencies has been sufficiently well standardized to make it readily usable even by persons who are not expert in optical technique. In this connection it may be well to point out that physicists as well as students of vision have, in general, erred methodologically in specifying stimuli in terms of wave-lengths rather than frequencies, since the latter remain unchanged throughout the process of propagation while the former may be modified radically by the media which the radiant energy is traversing. We cannot feel certain at present that the response of the retinal receptors is determined by frequency independently of wave-length, although this would seem to be the most reasonable supposition. At any rate the visual investigator should keep these two concepts clearly separated in his mind, and should regard wave-length measures as specifying, in general, the reciprocal of the invariable frequency numbers. The actual wave-lengths within the retinal rods or cones may be quite different from those which are employed to specify the spectral constitution of the stimulus outside of the eye.

One specific form of physical research upon radiation which is of particular importance to the student of vision is the spectrophotometric or spectroradiometric analysis of sunlight and daylight. It seems certain that chromatic vision revolves around solar radiation, as an origin of coördinates in its system of possible stimuli. The determinations made by Abbot of the solar spectrum under various conditions of time and weather furnish a very valuable set of data, but these need to be verified and amplified by further observations, representing not only a wider range of conditions but other portions

of the earth's surface outside of Washington, D. C.[85] Our understanding of the peculiarities of twilight and of artificial light vision will undoubtedly be greatly assisted by a knowledge of the exact manner in which daylight changes in spectral constitution throughout the day. Excellent work along this line has already been done by Priest, using colorimetric methods.

SECTION 9.—THE DIOPTRIC AND ALLIED PROCESSES OF THE EYE (STAGE THREE).

Our knowledge of the structure and operation of the normal eye, considered as an optical instrument, is in relatively a very satisfactory state. The general results achieved by Helmholtz upon this problem appear still to remain valid and to provide us with a sufficiently accurate understanding of the refractive processes which are involved in producing the retinal image.[86] Helmholtz's schematic or his "reduced" eye give us the means for determining quite exactly the sizes, shapes and positions of the retinal images formed by any pencil of rays—whether in or out of focus—which may be supposed to impinge upon the cornea. It is undoubtedly desirable to secure additional anatomical data, particularly data derived from measurements upon the living human eye, on the basis of which to establish the dimensions of the average normal optic mechanism for individuals of different ages and races; but these are by no means the salient problems of to-day in visual science. Our main task is to employ the ocular constants, which have been so reliably established, as implements in the investigation of processes which still remain essentially mysterious. Although Helmholtz's hypothesis as to the mechanism of accommodation is the only one which appears to fit satisfactorily all established facts, it still does not rest upon a foundation sufficiently firm to make it immune to attack. For this reason it is desirable that further experiments and observations be made bearing upon the accommodative adjustments. There can be no doubt, however, that such views as those recently advanced by W. H. Bates,[87] which attribute accommodation to changes in the shape of the eye-ball, are utterly fantastic, and the only question which remains is with regard to the exact details by which the changes in lens shape are brought about.

Although we may regard the general refractive processes of the normal human eye as having been satisfactorily established, the same cannot be said of the nature, the degree and the causes of the optical defects which are manifested either in the average or in characteristic abnormal eyes. Only recently, for example, have any careful studies been made upon the chromatic aberration of the nor-

mal eye. The work of Nutting,[88] and more particularly of Hartridge,[89] on this subject has opened up a very interesting and theoretically important group of facts. The work of Ames and Proctor on the spherical aberration and oblique astigmatism in various directions and meridians, of the normal eye is indicative of further, hitherto relatively uncultivated, fields of visual research. Ophthalmologists are constantly studying the defects of particular human eyes with a view to their correction by means of glasses, but regrettably little which is of scientific value has resulted from their observations. It is greatly to be hoped that some way will be found for bringing such ophthalmological data together for purposes of scientific generalization.

Aside from the systematic deviations of the refraction of the eye from those of an ideal optical instrument, we must consider also random aberrations of the rays within the eye which are of the nature of scattering. The study of the entopic phenomena which result from characteristic interferences with the course of light through the eye, due to particular anatomical or histological structures, has revealed the mechanisms of various processes of this character. The concentrically laminated structure of the crystalline lens is responsible for the "rays" seen on points of light against a dark background; general diffusion of light within the eye appears to result from the slight turbidity of all of the ocular media; and the highly specialized structures of the retina itself introduce many detectible modifications in the image. Much work remains to be done in this field, however. The recent investigations of Raman,[91] and of Sheard,[92] exemplify a fruitful method of attack upon certain problems of this sort. The purpose of such investigations is not only to provide us with a thorough knowledge of the intraocular adventures of radiant energy, but to enable us to establish accurately the qualitative and quantitative characteristics of the energy which reaches particular retinal receptors. Although most of this energy is directed by the normal refractive process, it is not at all certain that we can arrive at a correct analysis of the retinal functions without taking into consideration the effects of intraocular scatter, diffraction, and absorption.

One problem which is worthy on account of its systematic importance, of particular consideration is that of the selective absorption of the ocular media. If we wish to determine accurately the spectral character of the retinal image for any given object or stimulus, we must know the spectral distribution of transmission of the entire ocular material, lying between the front surface of the cornea and the retinal receptors. It is to be presumed that the two main constituents in the absorption system in question are the watery substance of the cornea, aqueous humor, lens, and vitreous humor, together

with the yellow pigment of the *macula lutea,* in central vision. The most important of these factors is the last. Hering and others have attempted to explain certain characteristics of the color excitation curves, both for normal and for color blind individuals, on the basis of assumptions regarding the magnitude or variability of the macular absorption. The present writer has found it possible to remove the asymmetry of the average, normal photopic, visibility curve by correcting for the selective absorption of the ocular media, employing Sach's [93] data on the transmission of the yellow spot. However, the statement is repeatedly made that the yellow pigment of the macula is a postmortem artifact. It is important, therefore, that the validity of this assertion be determined and that reliable measurements be made upon the selective absorption of the macula in human eyes as nearly as possible in the living condition.[94]

In our endeavor to deduce the characteristics of the retinal image from those of the stimulus and the optical structure of the eye, we must consider not only the refractive and other light-modifying processes in the ocular media, but the forms and positions of various parts of the retinal receptor surface in relation to the main axes of the eye. It is clear that the stimulus intensity, on any element of the retinal surface, will depend upon the angle which the latter makes with the direction of the rays and will also be influenced by the effective projected area of the pupil with respect to the position of the given element. The sizes, shapes, and dioptric properties of the individual receptors themselves must also be taken into consideration. The ellipsoid structures of the middle segments of the cone-cells undoubtedly serve to concentrate the rays upon the sensitive terminal segments. It is highly desirable that someone should plot out accurately the factors which interrelate the intensity of the retinal image for various wave-lengths with the corresponding intensities of stimulus or object points placed at various angles to the line of sight. Although we regard vision as a distance receptive sense, the actual physiological stimulus is the radiation which arrives within the terminal segments of the rod and cone-cells, and until we possess complete theoretical means for computing the properties of this ultimate retinal image at all points upon the retina, we are lacking in an essential basis for research upon subsequent stages of the response.

SECTION 10.—THE RETINAL STIMULATION (STAGE FOUR).

Our knowledge of the processes of stimulation, which occur when the radiation which constitutes the retinal image penetrates the substance of the rods and cones, is unfortunately derived by speculation

or inference. Nevertheless, certain generalizations appear to be well founded. Ranking first among these is the identification of the rods and cones themselves as the essential receiving elements. That the rods and cones are the primary retinal receptors is evidenced, not only by the fact that they are located at the very beginning of the visual conduction path, but by the structure of the *fovea centralis*, in which the basal and terminal segments of the cone-cells are the only retinal elements which bear a systematic relationship to the impinging light rays. A quantitative study of the entoptically observed shadows which are cast by the retinal blood-vessels upon the sensitive receiving surface, also indicates that this surface is localized in the stratum of rods and cones. Some room for argument appears, however, still to remain with regard to this question, certain writers, such as König, maintaining that the pigmentary epithelium is the seat of retinal stimulation while others, such as Edridge-Green, hold that the rods are not sensitive to stimulation. It is desirable that the measurements based upon a triangulation of points in the sensitive surface by means of the retinal blood vessels or other entoptically effective structures be carefully repeated. It would in particular be interesting to repeat the observations of König and Zumpft[95] in which stimuli of different wave-length constitution were employed. These latter measurements indicated that the positions of the sensitive surfaces for different spectral regions do not coincide, but the investigators mentioned appear not to have considered with sufficient care the part which may have been played by chromatic aberration in their observations. Assuming the validity of the many lines of evidence which point to the retinal rods and cones as the seat of visual stimulation, we find ourselves faced with the question as to the exact physical nature of this process. The objective lines of evidence which contribute to an answer to this question consist almost exclusively in the results of studies upon the electrical rest and action currents of the retina, and upon the retinal pigments. Psychophysical observations also provide valuable bases for inference and for choosing among alternative hypotheses.

The very convincing combination of psychophysical and anatomical evidence which has been built up by the work of Schultze, Boll, Kuhne, von Kries and others [96] seems to demonstrate beyond peradventure the duality of the receptor mechanism in the normal human eye. We cannot doubt, in the light of this evidence, that the retinal rods are organs of achromatic, low intensity (scotopic) vision while the cones are the vehicles of chromatic, high intensity (photopic) vision. It is to be expected, therefore, that further work bearing upon the functional differences between the rods and cones will strengthen rather

than weaken this so-called "duplicity" theory. Views such as those of Edridge-Green,[97] who regards the rods as non-photosensitive manufacturers of visual purple, which latter is operative only in stimulating the cones, may be dismissed at once without serious consideration. It must be recognized, however, that our knowledge of the functional and anatomical differences between the rods and cones is still capable of being supplemented by further studies. We possess quite a satisfactory map of the average retina but are lacking in adequate knowledge of the limits within which its structure may vary from individual to individual. The recent work of Abney[98] indicates that certain individuals may even have a small number of rods in the fovea, whereas it has hitherto been supposed that a region of about three degrees diameter in the center of the retina is entirely free from rods. Much remains to be done also in studying the physiologically observable changes which accompany light or dark adaptation.[99]

Our modern speculations concerning the visual receptor mechanism, which regard the latter as a photochemical process, find their principal empirical justification in the work of Kuhne[100] and his followers upon the visual purple of the rods. The close correspondence existing between the spectral sensitivity curves of this substance and of scotopic vision seemed originally to provide a firm basis for identifying the visual purple with the essential photo-receptive material of the rods. Observations upon animals whose rods possess no visual purple, or which can see when the purple has been destroyed have weakened this reasoning, so that at the present time the visual purple is often regarded merely as a supplementary sensitizer, augmenting the sensitivity of an essential receptor mechanism distinct from the pigments in question. In this situation it is indeed gratifying that so keen a worker as Hecht[101] should have taken up anew the chemical study of the visual purple and it is to be hoped that this study will again be energetically pursued.

The notion that, after all, the visual purple is merely a sensitizer is seemingly substantiated by the apparent absence of a pigment in the cones. However, existing data can scarcely be regarded as demonstrating the real absence of such a pigment. The fact that the cone sensitivity is less than one one-thousandth that of the rods indicates that the concentration of the cone pigment may be so very small as to elude detection by ordinary methods of observation. Moreover, psychophysical measurements show that cone adaptation to light is extremely rapid, so that although appreciable amounts of pigments may be present in the living eye they are almost wholly destroyed by the very processes through which we seek to demonstrate their exist-

ence. It is highly desirable that some capable biophysicist should attack systematically this problem of the presence or absence of a cone pigment, employing methods which avoid the criticisms attaching to previous, very superficial work upon this subject.

The host of speculations which have appeared regarding the mechanism of the retinal receptors have nearly all made use of the notion of *resonance,* to explain the selectivity of the retinal response. Such resonance has been conceived in mechanical, chemical, and electrical terms, and has been supposed to result in such effects as mechanical vibrations or waves, heat, chemical decomposition or recomposition, ionization, and electric currents. A moment's consideration of the excessively high frequencies which characterize the visual stimulus shows that resonance of gross mechanical or anatomical structures is out of the question; and that the immediately responsive elements must be of the order of magnitude of atoms, and that presumably they are electrons. On general physical grounds, there can be little doubt that the initial process in the retinal response is the ejection of electrons from atomic or molecular structures in the cell substance. Whether this electronic emission results, secondarily, in a photochemical change or whether it immediately manifests itself in the action current of the retina is a question which we cannot at present answer upon empirical grounds. The extremely high sensitivity of the retina suggests that the total process is a complicated one, possibly involving (as suggested by Hecht)[102] a catalytic system. Recent discussion between Lodge, Joly and Allen [103] has centered around the resemblance between the retinal response and the photoelectric effects in metals. Lodge has even suggested that radioactivity may be involved. Such lines of thought are interesting but have little permanent value unless they are pursued experimentally. It is greatly to be wished that some worker who possesses a balanced knowledge of physics and of physiology should attack this problem of the essential receptor process, applying the method of physical hypothesis—checked quantitatively by specially devised experiments—which has proved so fruitful in other lines of physical investigation.

Undoubtedly the most available line of experimental attack in such an effort is that afforded by measurements of the *electrical action currents* of the retina and of the optic nerve. The early work of du Bois Reymond, Holmgren, Kuhne and Steiner, Einthoven and Joly,[104] Piper,[105] Fröhlich[106] and others is now being superseded by the investigations of Bovie and Chaffee.[107] In general, the latter investigators verify the results obtained by their predecessors, but they have been able to eliminate sources of variation and error which accompanied

the older techniques. Their data indicate that the electrical response of the retina to light is a composite result of a number of superposed pulses. The respective reactions of the rods and of the cones in the frog's eye are readily separable by this method. Refinements of this technique may be expected to yield very definite results, especially if the experiments are carried out in the light of well-considered physiological hypotheses and established psychophysical data.

The electrical phenomena of retinal response leave little doubt that the ultimate mechanism of receptor stimulation is to some degree electrical in nature. The same conclusion can be reached by considering either the nature of nerve excitation in general, or the manner in which radiant energy must necessarily act upon matter. However, it is greatly to be doubted whether the retinal reaction can be formulated in electrical terms to the exclusion of chemical conceptions. On the whole, the notion of the visual receptor process as consisting in an electrolytic dissociation controlled by light intensity,[108] lends itself most readily to the formulation of an hypothesis which is consistent with all of the relevant facts. In endeavoring to work out details of such an hypothesis, the mathematical speculations regarding the laws of chemical response which have been advanced by von Kries,[109] Lasareff,[110] Nutting,[111] Pütter,[112] the present writer,[113] and others should not be forgotten.

Section 11.—The Afferent Nerve Excitation and Conduction (Stages Five and Six).

The Afferent Nerve Excitation.—It is natural that very little attention should thus far have been paid by students of visual physiology to the process by which the retinal activity is transformed into specific currents in the optic nerve fibers. There can be little doubt, however, that this process presents a problem which is as definite and as mysterious as that of the receptor mechanism itself. The modern, or Nernst-Lillie,[114] theory of the nerve impulse, together with the establishment of the "all-or-none principle" by Lucas and Adrian,[115] provide us with the materials for working out a conception of the optic nerve process. According to the Nernst-Lillie theory,[116] neural currents consist of series of unit pulses of depressed polarization and increased permeability which travel along the membranes surrounding the nerve cell. Nerve cells, in common with other biological units, carry on their surfaces in the resting state an electrical double-layer, which is due to the differential permeability of their boundaries to positive and negative ions, and which is responsible for the so-called "current of rest." The "negative variation" of this latter current, which goes with

excitation, is attributable to a momentary decrease in this surface electrification resulting from a general increase in the permeability of the cell boundary. The mechanism of the Nernst-Lillie hypothesis, as well as the empirical data of Adrian and Lucas, necessitates that apparent variations in intensity in a nerve current should consist in variations in the number of "all or none" pulses of excitation which pass through a given cross section of a nerve in unit time, and not upon changes in the magnitude of the individual pulses. Such variations in the "density" of these nervous quanta may depend upon alterations in the number of nerve-fibers simultaneously involved or in the frequency of the pulses in a single fiber.

The problem of the optic nerve excitation process reduces itself to that of the means by which presumably continuous variation in the intensity of the retinal receptor reaction can be transformed into gradations of nerve pulse density in the optic fibers. Moreover, it is required that the photochemical or other activity occurring in the rods and cones should be capable of bringing about alterations in the polarization or permeability of the attached nerve conductors. The present writer has suggested a possible mechanism,[117] harmonious also with other facts in the case, which meets these two sets of requirements. Further evidence will undoubtedly demand modifications of this proposed view.

The Afferent Conduction.—No attempt will be made here to review in detail the established anatomical facts regarding the course and interconnections of the optic nerve conductors, which lead from the retina to the cerebral cortex and lower brain centers. It is necessary, however, to emphasize the great systematic importance of an exact knowledge of this conductional topography for our understanding of the visual process. From the retina to the brain and hence from the retina to the visual consciousness, the process of seeing depends upon an extremely intricate telegraphic system. It is essential that we should determine the "wiring diagram" of this system for human beings and for any animal species, the visual processes of which we may be studying. It may be regarded as established[118] that in man the right halves of the two retinas are connected with the right hemisphere of the cerebrum (in the occipital region) while the left retinal halves are connected with left cerebral hemisphere. This interconnection is brought about by means of a crossing over of approximately half (semi-decussation) of the fibers of each optic nerve at the chiasma to the opposite side. The fibers supplying the centers of each retina are apparently gathered into special bundles and, although

they undergo semi-decussation at the chiasma, the distribution of fibers in this crossing over is evidently such as to permit the whole area of each retinal center to be connected with both cerebral hemispheres. In general, complete decussation of the optic fibers is the rule in the animal kingdom, the direct, or non-decussated, conductors being associated with a positioning of the two eyes in the head such as to permit of binocular vision, although the correlation between these two features is not perfect. Passing through the optic chiasma there are also fibers which connect one retina with the other and also centrally connected commissures (Gudden's commissure). The optic tracts, proceeding from the commissure and carrying the essential visual fibers, divide each into three branches, the principal branch connecting, through the external geniculate body and the central visual tracts on either side of the head, with the visual cortex of the cerebrum. Another branch passes to the anterior quadrigeminate body, where it connects through synapses with the oculomotor nucleus and *via* this with cells in the tegmentum, which in turn are connected by efferent fibers with the visual cortex.

Through this complex path must pass those disturbances in electrical and molecular equilibrium of the component nerve fibers which constitute the visual conduction process. This conductional activity must be sufficiently refined and differentiated to enable it to convey to the cerebrum representations of all important characteristics of the retinal image, if the objects of vision are to find adequate correlatives in the visual consciousness. Psychophysical analysis shows that within each unit conducting path at least three independent variables must exist corresponding with the three components in trichromatic vision. In the light of the all-or-none principle, it seems difficult to see what these three modes of variation can be. Although the all-or-none principle permits of intensity variation along any single fiber, in terms of the frequency of unit pulses passing a given point per second, it seems to preclude any thought of multiplex conduction. Evidence now at hand indicates that in the center of vision at any rate all three visual components can be transmitted to the brain along a single nerve fiber. Whether the evidence upon which this belief is founded is adequate or not may still be a question but "the three nerve fiber theory" of Helmholtz seems to have been definitely abandoned.[119] Clearly, therefore, one of the most interesting problems facing the visual investigator at the present time is that of the mechanism by which the trichromatic analysis of the stimulus which is presumably effected by the receptor, is reported to the cerebral cortex. In attempting to work out a solution of this problem, we should re-

consider very carefully the evidence against Helmholtz's original three-nerve fiber hypothesis, and should take into consideration all established facts with regard to the interconnection and interactions of closely adjacent components in the visual conduction system.

Because of our inability, using available methods of investigation, to determine the nature of the central visual process we are forced to rely upon psychophysical observations as a basis for nearly all of our reasoning concerning the central and conductional activities. Among other problems which are thus suggested is that of the conductional basis of binocular fusion. Since homonymous halves of both retinæ are connected with the same half of the cerebrum it would be natural to suppose that corresponding points of the two retinæ are represented in the visual projection areas of the cortex by single synaptic points. The singleness of vision which accompanies the simultaneous use of both eyes would then be explained in terms of the unity of the central process. However, Helmholtz,[120] Sherrington,[121] Dawson,[122] and others have argued, on the basis of special psychophysical data, that such fusions of the nerve currents emanating from corresponding retinal points do not in fact occur. These writers regard binocular fusion as being essentially a psychical function. This view seems to be so subversive of the most approved psychophysical, as well as physiological principles, that the facts and arguments upon which it is founded should be carefully reconsidered.

Igersheimer[123] has recently disputed the generally accepted view that the arrangement of the fibers in the optic nerves corresponds approximately to that of the retinal elements with which they are connected. He maintains that injuries to the optic nerve tend to produce scotomas centering in sector form about the blind spot. In the opinion of Hoeve,[124] Best[125] and other authorities, however, this contention is incorrect. In general, it appears that much remains to be done in tracing out what may be called the *correspondence of patterns* between the various successive stages in visual response. If we start at the retina with a circular pattern of stimulation, what will be the exact form taken by the corresponding nerve currents at various cross-sections in the optic nerve, optic tract, and visual projection areas? Ultimately we should be able to answer this sort of question for any given geometrical configuration of the stimulus. Our ability so to answer must obviously depend upon an acquaintance with the precise manner of interconnection or redistribution of the visual conducting elements. No doubt there is a certain amount of variation in this distribution of conduction among individuals, but we should eventually be able to establish reliable norms.

In general, it is greatly to be hoped that attempts will be made, at least on animals, to study the visual conduction processes at various levels by the direct method of observing action currents. In order that such studies should yield reliable results it will of course be necessary to refine the technique much beyond present achievements along this line but beginnings are apparently being made in such studies by MacPherson[126] and others.

Section 12.—The Central Processes in Vision (Stage Seven)

As already noted, the demarcation of the central stage in visual response, from afferent and efferent conductional stages is a more or less arbitrary matter. All of the central activities are essentially conductional in their function. For our present purposes we may choose the visual processes which occur in the cerebral cortex as constituting the essential central stage or stages. Subcortical synaptic and adjustor processes, which involve the transfer of nerve currents from afferent to efferent channels, will be considered briefly in connection with the corresponding oculomotor phenomena. In considering the cerebrocortical processes which are involved in vision or probably in any other sense, it is necessary in the beginning to rid ourselves of the notion that we are dealing with a simple or unitary mechanism. There can be little doubt, in the light not only of the general requirements of the case, but of established psychophysical facts, that visual conduction through the cerebral cortex involves a very elaborate series of operations, entailing on the one hand the synthesis, through successive phases, of multitudinous afferent currents or sensory data, and on the other hand the coördinated regulation of a complex array of efferent mechanisms. The visual consciousness appears to be determined by only one of these successive stages of integration or control, presumably by a focal process which involves the synthetic functions to the maximal degree. It is fairly clear that the visual consciousness does not depend directly upon processes occurring in the visual projection areas, but is associated psychophysically with higher association area operations.

It is the first stage only, in an elaborate series of cortical operations, which occurs in the visual projection areas. The multitude of psychophysical observations which were made during the recent war, on the correlation between projection area lesions and consciousness, have amply confirmed Henschen's notion of the approximately point to point correspondence of the visual cortex and the retina, completely disposing of von Monakow's idea of the diffuse distribution of retinal connections in the projection regions.[127] The researches of

Morax,[128] Moreau, Castelain,[129] Monbrun,[130] and others also indicate clearly that the foveas of both retinas have a representation upon both cerebral hemispheres. The upper zones of the retina appear to be connected with the upper portions of the corresponding visual projection areas, the middle retinal zones with midportions of the projection areas, and the lower retinal zones with the lower parts of the areas in question. The projection areas proper are confined to the mesial surfaces of the calcarine fissure, the representation of the *macula lutea* lying in the anterior region of the fissure according to older views, but in the posterior region according to the more recent findings of Monbrun and of Morax. According to the views of Morax, Moreau and Castelain, although the foveas are represented upon both cerebral hemispheres, the remaining macular region has a divided representation, like the retinal periphery.

Psychophysical observations indicate that the fundamental visual functions of form perception, color, and light discrimination, and also the essentials of binocular fusion or localization, are mediated in the calcarine fissure at points within the visual area coinciding with the points of projection of the nerve currents to which these functions refer. However, the fact that the functions in question can be independently affected in pathological conditions indicates that they possess distinct mechanisms, and that in all probability we have to do with distinct processes in various strata of the calcarine cortex. Other psychophysically higher visual functions, such as motion perception, contrast, visual recognition, perception and imagination, and some aspects of color sensibility, seem to depend upon occipital areas which envelop the calcarine region. The existence of visual hallucinations in cases of cortically produced blindness shows that the projection areas and closely associated neurones are merely way-stations The facts of visual aphasia and allied disorders also demonstrate the importance of higher cortical centers in the entire visual process. The laws which govern the visual hallucinations and psychic blindnesses in hysteria, war-shock and other psychoneuroses, show that the very highest associative functions can exert a powerful influence upon the factors which control the visual consciousness and hence voluntary behavior.[131]

The complexity of this subject obviously makes it impossible to outline in detail the many specific problems which remain to be considered experimentally regarding the cortical visual functions. The reader is referred to an article by Best for a very suggestive review of these problems.[132] We stand here, apparently, at the very focus of the psychophysical relationship and hence in a domain where re-

sults are of the utmost theoretical importance, but in which unfortunately they are difficult to secure. In general, it would seem important to insist that the visual processes of the cortex are highly complex and yet at the same time mechanically definite. We should endeavor to analyze out and to determine the modes of interrelationship of the unit functions which are in all probability successively involved in the propagation of the visual nerve currents through the cortex. We should be prepared to find that these unit functions do not correspond accurately with preconceived analyses, based upon our notions of sensory or receptor physiology. In general, as indicated by analogous work of Head upon the cutaneous senses, the lines of demarcation between physiological components in the cortical activity will correspond more closely with higher psychological than with sensory constituents or classifications.

SECTION 13.—OCULOMOTOR MECHANISMS (STAGES EIGHT *et seq*).

It is highly probable that, in the normal individual, all voluntary movements are under the influence of visual impulses. Even in the dark, visual imagery plays an important rôle in consciousness and may be regarded as an index of concomitant, cortical, visual factors. It is a familiar fact that in diseases of the proprioceptive system such as locomotor ataxia, visual impulses may become the sole sensory basis for motor regulation, which previously was mainly controlled by nerve currents from the receptors of the muscular system. Behavior based upon visual data undoubtedly differs in its exact character and mechanism from that which is regulated by other species of afferent impulses. It is obviously a part of the whole problem of visual science to work out the mechanisms by which visual impulses, operating through the complicated afferent apparatus of the optic nerve and visual projection areas, are able to control the innervations of the pyramidal, efferent neurones in the motor projection area of the cortex, which determine coördinated movements of the skeletal muscles. Here are problems galore for the psychological "behaviorist" as well as for the neurologist who is interested in the "integrative action of the nervous system."

However, we must confine ourselves to a few remarks upon the essential ocular movements and their corresponding mechanisms of innervation.

Accommodation.—The ciliary muscle which controls accommodation is innervated by the third cranial or oculomotor nerve, which arises, together with the fourth or trochlear nerve, from a synaptic nucleus below the aqueduct of Sylvius near the anterior corpora quadrigemina.

The studies of Bernheimer[183] upon the monkey show that this oculomotor nucleus is divisible physiologically into a very considerable number of subordinate nuclei. Bernheimer divides these subordinate nuclei into the principal and the accessory nuclei, and believes that the latter are responsible for the regulation of the internal ocular muscles (i. e. those of the iris and the lens control). All of these nuclei have a bilaterally symmetrical structure, the two corresponding portions being connected either by crossed or direct fibers with the respective eyes. The oculomotor nucleus receives afferent fibers from the retina and efferent ones from the visual cortex, involuntary or reflex movements depending wholly upon the former whereas voluntary movements are directed by impulses through the latter set of fibers. Little or nothing is known concerning the exact nature of these innervations and of the physiological properties of the corresponding nuclei which underlie the extremely accurate and rapid adjustments of the eye muscles.

Helmholtz attributes the bulging of the anterior surface of the lens, which occurs in accomodation, to the inherent structural elasticity of the lens itself, the lens in the unaccommodated state being flattened by the tension exerted upon it by its capsule and the suspensory ligament. The contraction of the ciliary muscle is supposed to relieve this tension. Although this hypothesis appears to be well substantiated by established facts, there is still considerable uncertainty as to the exact manner in which the contraction of the ciliary muscle is able to release the tension upon the ligament. Further work upon the details of the accommodative mechanism is greatly to be desired.

Pupillary Control.—The iris contains two functionally antagonistic sets of muscles which respectively constrict and dilate the pupil. As above noted, the fibers which innervate the constrictors are a part of the oculomotor nerve and arise in or near the oculomotor nucleus. The dilator fibers on the other hand are derived from the ventral root of the eighth cervical and first thoracic nerves and are part of the cranial sympathetic nervous system, the corresponding nuclei lying in the cervical region of the spinal cord. As a result of the many elaborate and accurate investigations which have been made of pupillary reflexes, our knowledge of its action may be regarded as relatively complete; although there is, of course, plenty of opportunity for research upon the physiological details of its complex innervations and the peculiar properties of the iris tissues. The recent work of Reeves[185] provides us with a very exact analysis of the rates of reaction of the iris to definite light intensity changes. The reflexes which associate the pupillary reaction with accommodation and with

convergence have also received considerable attention, but a great deal still remains to be done upon this subject. Extant results indicate that the light reflexes of the iris depend upon afferent impulses derived from the cones only, the rod process having no connection with the pupillary mechanism.[136] We are lacking in exact knowledge of the manner in which pupillary reactions depend upon factors of size, intensity and position of the stimulus upon the retina as well as upon adaptation, both photopic and scotopic. The relationship between indirect or consensual and direct pupillary reflexes also requires further quantitative examination.[137] There is some evidence that the afferent fibers which govern the pupillary reactions are distinct from those which transmit the visual impulses to the higher centers.[138]

Movements of the Eye-balls.[139]—Each eye-ball is provided with four muscles arranged in antagonistic pairs for rotating the eye about approximately horizontal and vertical axes respectively. In addition there are two "oblique" muscles which rotate the eye-ball around the line of sight. These muscles are innervated by the third, fourth and sixth cranial nerves, the superior oblique muscle being associated with the fourth, and the external rectus muscle with the sixth nerve. The reflex center for these nerves consists of the so-called principal nuclei of the oculomotor nucleus except in the case of the external rectus, which is connected with the special nucleus of the sixth or abducens nerve.

The kinematics and dynamics of ocular movements have received a great deal of attention in the hands of Helmholtz and later thinkers, the mathematical treatment of these movements being extremely complex. The recent contributions of Lamb[140] to this subject show that there is still room for theoretical progress in the mathematical analysis of ocular movements. Dodge[141] originally distinguished the following five types of ocular adjustments: (1) Reactions to excentric retinal stimulation. The purpose of these movements is to bring the object of regard into foveal vision. During such movements no perception takes place, their sole function being to move the line of regard to a point of interest. (2) Pursuit movements occur whenever the eye follows a moving object. Unlike movements of the first type, pursuit movements give moments of clear vision. Such movements show no periods of rest and, therefore, involve a continuous activity of the eye muscles. During such pursuit movements the line of regard tends to lag behind the moving object, which lag is intermittently corrected by jerky movements of the first type. (3) The third type of eye movement occurs whenever the head moves while the eyes retain a fixed point of regard. They adjust themselves to all changes in the position

of the head without measurable lag. (4) Whenever a subject is rotated in a revolving chair while his eyes are closed there occur a number of jerky compensatory movements of the eyes. These jerks differ from those involved in type 2 and their function is as yet somewhat obscure. (5) The fifth type consists of movements of convergence and divergence. It is a reaction to an extrinsic stimulus which falls on disparate parts of the retina and the movements of the two eyes are consequently not in the same but in opposite directions. In contrast to movements of the first type, these permit of accompanying perception and are much less rapid than adjustments of the first type. Dodge[142] has also made a very thorough study of visual fixation.

Bernheimer has traced out in considerable detail the mode of innervation of the several eye muscles.[143] In dealing with this question we must explain not only the closely coördinated movements of translation or of convergence of the two eyes, but also the reciprocal innervation of the antagonistic muscles which is required in all ocular movements. Voluntary displacements of the eyes are apparently innervated from the angular gyrus of the cerebral cortex. It seems that ocular movements are regulated not with respect to proprioceptive impulses, but mainly with respect to the positions of definite images upon the retina, or their representations within the visual projection area of the cortex. The study of the nature and mechanism of ocular coördination, depending either upon voluntary or involuntary processes, is one of the salient problems in this domain at the present time. This problem is closely bound up with that of binocular stereoscopic vision, although the latter, at least in the form in which it is ordinarily discussed, is a psychophysiological problem. The relation of ocular movements to stimulation of the semicircular canals of the inner ear, including the study of nystagmus of various types, also presents a fertile field for further investigation.[144]

Other Ocular Reactions.—The eyelid reflex must also be considered as a visual adjustment, particularly in view of the fact that it is controlled through the oculomotor nerve and its nucleus. The palpebral muscles are under the control not only of the cortex, but of the retina and of the ear operating *via* subcortical centers. Although the eyelid reactions are apparently simple, there is considerable uncertainty as to the degree in which they are dependent upon learning. Lachrymation, although a glandular process, must also be regarded as a visual effector activity. It goes without saying that there is plenty of room for work upon either of these seemingly primitive ocular reactions.

CHAPTER V.

THE SALIENT PROBLEMS OF VISUAL PSYCHOPHYSIOLOGY

The problems of visual science which have attracted the most attention have as a rule involved psychophysical correlations. Such correlations, in general, have referred to the visual consciousness on the one hand and to known factors in the physiological response system on the other hand, such factors usually being located in the peripheral stages, afferent or efferent, of the response. In the majority of instances, the complete physiological or psychophysical mechanisms underlying the psychophysiological correlations in question remain unknown, although plausible conjectures as to their nature have been advanced. In our preliminary discussions we have considered in sufficient detail the nature of psychophysiological correlation in general, so that we may proceed at once to review briefly the salient phases of visual psychophysiology.

SECTION 14.—BRILLIANCE VISION (PHASE A).

Important among the problems of visual psychophysics are those which involve determining the relations or functions which hold between the three attributes of *color* (brilliance, saturation and hue) and a multitude of factors in the response system. We may consider first the physiological relationships of *brilliance.*

Brilliance and Wave-Length.—This attribute, the apparent brightness of visual objects, is ordinarily regarded as an index of the intensity of the stimulus. However, the correlation between brilliance and intensity is on the whole less definite than that between brilliance and wave-length. An analysis of this latter relationship discloses in general a bell-shaped curve, if wave-length is taken as the abscissa and brilliance as the ordinate. The exact form of this curve, however, depends upon the level of stimulus intensity and the state of adaptation of the visual system. Using the method of psychophysical brilliance equations and plotting as ordinates the reciprocals of the intensities required for equal brilliance at different wave-lengths, we obtain for high intensities and daylight adaptation the so-called visibility curve which has a maximum at 556 $m\mu$ and values of 0.01 at 429 and 687 $m\mu$. If this curve is determined for radiation intensities outside of the eye, it is slightly asymmetrical in form, being depressed on the short wave side, but if it be corrected for the selective absorption of the ocular media it becomes practically symmetrical and fits the probability function very closely.[145] The elaborate measurements

which have been made by American investigators,[146] in order to determine the average normal visibility curve, may be regarded as establishing this relationship for daylight vision with a precision much greater than has yet been attained in any other psychophysical function.

It should be noted, however, that the visibility curve is not, strictly speaking, a plot between brilliance and wave-length. Because of the logarithmic relation which exists between these two variables, the form of the true brilliance-wave-length function will evidently vary for different intensities while its axis remains in a constant position.

Another change in the shape of the brilliance-wave-length function is noted at low intensities with dark adaptation, this latter change involving a shift in the position of the axis of symmetry, together with a radical displacement of the limits of visibility, involving a greater loss of brilliance at the long-wave than at the short-wave end of the spectrum. The maximum for this low intensity curve lies at approximately 510 $m\mu$ and the limits roughly at 420 $m\mu$ and 610 $m\mu$, respectively. It is highly desirable that this scotopic visibility or brilliance-wave-length curve should be determined with an accuracy equal to that which has been attained for the corresponding photopic curve. It is also important to ascertain more exactly than has hitherto been done the law of transition from one curve to the other, involving quantitatively specified alterations in the intensity and adaptation levels.[147] It is certain that studies of this sort are practically worthless unless both adaptation and intensity are carefully controlled, and it would be very interesting to know the modes of transition between the two curves with fixed intensities and variable adaptation and *vice versa*. The original studies of Kuhne showed a very close similarity between the visibility or luminosity curve of scotopic vision and the bleaching or absorption curves of the visual purple and the rod pigment. It is to be hoped that Hecht or some other modern worker will repeat this comparison.

There is at the present time practically no doubt that the scotopic visibility curve depends upon the isolated functioning of the retinal rods, whereas the photopic curve rests almost exclusively upon the response of the retinal cones. Accordingly, the scotopic curve is not ordinarily obtained in the center of the visual field. However, Abney's apparent discovery of the existence of a slight amount of rod vision in the center of the field for certain observers makes it important that statistical studies be initiated to ascertain the exact proportion of the population exhibiting this anomaly.

The exact forms of the limiting photopic and scotopic, brilliance-wave-length, functions, also, of course, vary considerably from individual to individual, such deviations from the normal being particularly marked in certain types of color-blindness. The statistics of these deviations are of great interest as bearing upon the systematic relationships of color-blindness and other anomalies to the normal. Data upon these points are still much needed.[148] The determinations of visibility functions have been made by a considerable number of methods—flicker, direct comparison, cascade comparison, acuity criteria, etc.—and numerous studies have already appeared on the interrelations of results obtained by the various methods.[149] Such studies should be continued, as they have a bearing upon the definition of brilliance itself as well as upon its psychophysical basis.

Brilliance and Stimulus Intensity.—The determination of the correlation existing between brilliance and intensity is complicated not only by the influence of wave-length, but by the effects of adaptation and of contrast. In practice, it is difficult to establish a zero point for brilliance at absolute black, since the latter is realizable, if at all, only under the influence of excessive contrast. It is more practicable to attempt to plot brilliance in number of just noticeable intervals above and below the gray which goes with an externally unstimulated retina, in equilibrium adaptation to darkness. Under these conditions we have zero stimulus intensity, but a very considerable degree of brilliance. By the introduction of outlying contrast fields we can decrease this brilliance towards the limiting perfect black, approximations to this limit being roughly proportional to the brilliance of the contrast sensation. On the other hand, by the introduction of increasing intensity in the test field itself, the brilliance can be increased in the direction of a perfect white. Chromatic characteristics may be present concomitantly without greatly complicating the result. In attempting to step off the total brilliance scale in this manner, it is clearly necessary to differentiate between the influences of intensity and of adaptation, since the latter process tends to follow intensity closely and to reduce its effects. It would be desirable to work out the brilliance scale both above and below the "idioretinal gray," holding the intensity constant, and altering the adaptation and *vice versa,* as well as to ascertain a similar scale for equilibrium adaptation at each intensity step. In view of the intimate relationship of these various factors the findings of Külpe and of König,[150] indicating, respectively, 800 and 660, just noticeable brilliance steps between black and white are probably of little significance. All of this work needs to be repeated

in the light of modern psychophysical analyses of the visual system.

Similar considerations apply to the formulation of such psychophysical data according to the schema of Weber's or Fechner's laws. How does the approximately logarithmic relationship between brilliance scale number and intensity, with its upper and lower deviations, itself depend upon adaptation and contrast? Recent investigations by Schjelderup[151] exhibit this law as a special case of a far more general principle in which the contrast situation plays a very important rôle. Bell claims that the lower deviations from logarithmic relationship disappear if the visual system is permitted to attain equilibrium adaptation to the lower intensities. Studies of these dependencies have been begun by Nutting,[152] Blanchard[153] and others. The earlier determinations of König and Brodhun[154 155] are still interesting, but the conditions under which they were made are inadequately specified.

Great interest attaches at the present time, in view of the quantum theory of radiation, to the magnitude of the absolute visual threshold. Careful measurements have been recorded by Abney,[156] using photometric units, of the threshold at the various wave-lengths. Blanchard[157] has ascertained the threshold as a function of the intensity level of adaptation, but this work needs to be carried further, employing the latest methods for the measurement of radiant energy and with meticulous attention to all of the conditions of observation. It is particularly to be desired that the absolute threshold for various areas of retinal stimulation should be determined for the rods and for the cones independently, using the wave-lengths to which the two sets of receptors are respectively most sensitive.[158] In the determination of absolute thresholds, the interrelations of intensity, area and time of exposure are of the utmost interest, since it appears that within certain limits these three factors are mutually equivalent, the threshold depending upon their product only. Piéron,[159] pursuing the problem previously attacked by Riccò, Charpentier, Loeser and others,[160] has recently published beautifully precise analyses of certain aspects of this relationship, indicating its definite dependence upon position in the visual field and the relative degrees of participation of rod and cone function.

Brilliance and Purity.—There has been considerable discussion in times past as to whether the photometric values of two visual stimuli of different wave-length composition could be added arithmetically to yield the photometric value of their mixture. The work of Ives[161] and other modern investigators indicates the validity of this "additive

combination of luminosities," for isolated cone vision and for the methods of photometric measurement which these investigators employed. On account of the technical importance of this question, as well as its theoretical significance, it is desirable that very careful studies should be made upon it, using a comprehensive array of wave-lengths and all of the practicable methods of photometric equation. It should be noted in this connection that the addition of luminosities or of photometric values does not involve an addition of brilliances since, at least approximately, the latter are proportional to the logarithms of the respective luminosities. In the interest of clearness it would be worth while to work out the additive principle, in relation to its consequences expressed in terms of brilliance for rod and for cone vision at various levels of adaptation.

SECTION 15. CHROMATIC VISION (PHASE B).

The word *chroma,* as it is employed in the present monograph, designates color in the restricted sense of the word, or the chromatic aspect of color in the general sense. Chroma consists of two attributes, hue and saturation.

Chroma and Wave-Length.—The relation between chroma and wave-length, of which hue is ordinarily regarded as an index, has been studied very carefully by Jones[162] and Steindler.[163] This work is employed by Jones in the definition of a "hue scale" and the spectral colors are plotted in terms of this scale as a function of wave-length. It is to be noted, however, that Jones' scale is not one of pure hue, but of combined hue and saturation change, since the various spectral colors are not of equal saturation. It is therefore greatly to be desired that determinations of a true hue scale should be made employing stimuli which would yield the various hues in equal saturations. Such stimuli, of course, would only in isolated instances be of spectral purity. The spectral chroma scale of Jones, of course, needs to be amplified by a careful determination of the number of hue steps through the purples, together with a study of the stimulus ratios required for the successive threshold differences which are involved. Professor F. O. Smith is at present working upon this latter problem. In general, it may be noted that a large opportunity for accurate and systematically significant work exists in the attempt to map out just noticeable intervals of hue and saturation in the psychological color solid.

The relations between saturation and wave-length which are involved in this system have received very scanty attention. Too often

the error (stimulus error) has been made of assuming that the complete physical purity of the spectral stimuli guarantees the equal saturations of the corresponding colors. A purely qualitative examination of the color spectrum, however, disposes of this notion at once, since it is clear that the spectral yellow is far less saturated than the blue or red. A systematic attack upon this problem would, of course, demand the determination of the number of just noticeable saturation steps lying between each spectral color and white. The writer understands that Ferree and Rand have made such determinations, as yet unpublished. There are, however, other measures which serve at least as indices of differences in saturation. Helmholtz[164] has already drawn attention to the wide difference which exists between the chromatic valences of different spectral stimuli in color mixture systems, the spectral blue, for example, exhibiting a very high ratio of chromatic power to brilliance, while its complementary, yellow, exhibits an extremely low ratio of this sort. The "flicker photometer frequency" of spectral colors[165] also furnishes similar indications.

All of these relationships, both of hue and of saturation, of course, need to be examined at a number of different intensity levels, presumably in groups having uniform brilliance but varying in chromatic characteristics. The relations obtaining between hue and saturation on the one hand, and wave-length on the other, should be considered carefully in their bearing upon theories of color vision and the three-color excitation curves. In this connection, the deviations from normal which occur in hue or saturation scales for color-blind or color-weak individuals are of the utmost interest. Another problem which is of theoretical importance in this field is that of the positions of the so-called psychological primaries in the hue scale and also the wave-length composition of their stimuli for the average normal individual. Westphal[166] has determined the wave-lengths for the psychological yellow, green, and blue as 574.5 $m\mu$, 505.5 $m\mu$, and 478.5 $m\mu$, respectively, the psychological red corresponding to the extreme spectral, long-wave, stimulus plus a small quantity of short-wave radiation. It would be interesting to have similar determinations made upon the typical forms of partial color-blindness.

Chroma and Intensity.—Both hue and saturation vary in a radical manner as functions of intensity. As in the case of the relations existing between brilliance and intensity, it is difficult but important to separate the effects of adaptation from those of intensity pure and simple, since the adaptation itself is a function of intensity provided time is allowed for adaptation to ensue.

With regard to hue, extant data indicate that with increasing stimulus intensity but fixed wave-length constitution, all reddish and greenish colors, with the exception of those having psychologically primary red and green hues, tend to become relatively more yellowish or bluish, in harmony with their low intensity tendencies towards these latter hues, respectively.[167] The psychologically primary yellows and blues do not change in hue with increasing intensity. However, all of the colors, including those of psychologically primary hue, decrease in saturation with augmented intensity and at the very highest intensities all stimuli yield a white or gray. The significance of this latter statement, however, is limited by our inability to obtain very high intensities of stimulation with radiation of low visibility, such as the extreme spectral wave-lengths. Extant data do not permit us to determine to what extent these changes in chroma depend directly upon intensity or to what degree they are dependent upon concomitant adaptation.[168] It is well established that exactly similar alterations in chroma occur as results of adaptation changes alone. This whole problem needs to be examined anew with very careful attention to the part played by chromatic and achromatic adaptation. It should also be carefully considered whether the "invariable" hues which appear in this relationship actually correspond with the psychological primaries. It is to be noted that there is a systematic similarity between these effects of increasing intensity and those which accompany the displacement of the stimulus from the center towards the periphery of the retina. All of these data, of course, have an important bearing upon the boundaries of the psychological color solid.

The decrease of intensity below a certain luminosity value is ordinarily considered to involve a reduction in saturation of the colors which are evoked by stimuli of given spectral composition, so that at very low intensities a gray is obtained. This effect, however, appears to depend upon the replacement of cone response by rod response at very low intensities, since reds do not exhibit it and it appears to be absent, at least relatively, in the center of vision.[169] In general, since the rods yield an achromatic color, it seems very essential to determine carefully the relative participation of rods and cones, in all studies upon the psychophysiology of saturation, the latter attribute showing an increase, other things equal, with an augmented ratio of cone to rod response. In general, we seem forced by facts already established to regard the cones as exclusive organs of chromatic vision.

Chroma and Purity (*Wave-Length Composition*).—The relations existing between hue and purity, or wave-length composition, are

summarized for the normal eye in the so-called color-mixture triangle,[170] a diagram which it is very important not to confuse with the psychological color solid. The color-mixture triangle indicates that for the normal eye all possible hues can be matched by the mixture of appropriate proportions of three, properly selected, elementary stimuli. From the physical point of view, these stimuli may or may not be homogeneous. The color-mixture triangle also shows within what spectral regions these three stimuli must be chosen in order to yield the required result. Within these rather broad regions, the choice is arbitrary unless some further criterion is introduced. The possibility, thus demonstrated, of matching any desired hue by a mixture of three elementary stimuli lies at the basis of so-called trichromatic colorimetry and three-color photography. Scientifically, the most interesting set of hue equations are those established between mixtures of three given elementaries and each of the spectral colors. A graph showing the amounts of each elementary required for different wave-lengths over the spectrum yields the so-called three-color excitation curves, upon which the Young-Helmholtz and allied color theories are founded. Such curves are ordinarily plotted so that their areas are equal, it being postulated that equal amounts of the three elementaries shall yield white or gray. If the curves are plotted in luminosity units the areas are very far from being equal, that for the short-wave excitation being, relatively, very small.[171] These same data, when plotted in the color-mixture triangle, yield the locus of the spectral colors within this system. The color-mixture triangle may be regarded as a section, ordinarily taken perpendicularly to the axis, of the solid angle enclosed between three mutually perpendicular planes with respect to which three-color mixture data are plotted in accordance with Cartesian principles. The three-dimensional plot provides a representation of the absolute values of the elementaries, whereas the triangle merely shows their proportions; but the latter are all that are necessary for chromatic psychophysical analyses at any given intensity level.

It is greatly to be desired that before long a careful and systematic redetermination of the three-color excitation curves for the normal eye should be made. Only three systematic determinations have thus far been recorded, those of Maxwell,[172] of König and Dieterici,[173] and of Abney.[174] All of these may be considered out of date on account of improvements in methods and conceptions since they were made. Maxwell's determinations are practically valueless at the present time, while those of König and Dieterici involved a number of ques-

tionable points of technique and utterly neglected the luminosity aspects of the problem. Abney's investigations were made from a more comprehensive point of view, but are far from being above reproach technically. E. A. Weaver has reduced the results of König and Dieterici and of Abney to comparable terms and finds that it is legitimate to combine them into an average set of values.[175] These average values provide us with the best information which is at present obtainable regarding the three-color mixture system of the normal eye. In planning a redetermination of these extremely significant values the most important factors which need to be taken into consideration would seem to be the following: (1) Instrumental errors such as those arising from scattered light in spectrometer systems must be reduced to a minimum. (2) The choice of elementary stimuli employed in the actual experiments, or to terms of which the results are ultimately reduced, should not be arbitrary but should be dictated by definite criteria, derived from other observations upon psychophysical relations of color, for example, the hue scale or the invariable hues in the intensity-fatigue relationship. (3) The photometric measures of the proportions of elementary stimuli employed should be carefully determined, along with the visibility curve of each observer. (4) The work should be done upon a considerable number of observers, both normal and abnormal, in order to provide a really statistical result. (5) It is needless to say that the determinations should be made upon partially color-blind individuals of the various types and that the results obtained with such individuals should be compared carefully with those yielded by the normal. Mr. Weaver and the present writer are planning eventually to make such a redetermination of the three-color excitation functions, but do not wish to be understood as preëmpting the field, as a number of researches upon this very important problem would not be inopportune.

Another color-mixture question which might be studied in conjunction with that of three-color analysis, or independently, is that of the *complementaries* of spectral stimuli. A number of investigations have been made upon this problem by König, Angier and Trendelenburg, and others,[176] but all of these researches suffer from an indefiniteness in the specification of the white, or achromatic color which was employed. In determinations of complementaries or, for that matter, of the three-color excitation values, a "white" of definite spectral combination should always be employed. Daylight and skylight are so extremely variable as to render experiments in which they are employed as standards seriously inaccurate. The best tentative definition

of a white or gray would appear to be the color yielded by a stimulus having an intensity distribution with respect to wave-length like that of a black body at 5200° K.[177]

Closely associated with these problems is that of the *saturation scale,* which involves determining the number of just noticeable saturation differences which separate each of the spectral colors from white, through a series of colors having an invariable hue. The problem of ascertaining the number of steps for each spectral color is to a certain extent independent of that of the physiological or physical conditions underlying each such series of colors.[178] It is clear that an indefinitely large number of ways exist in which a spectral color can be desaturated by adulteration of the homogeneous spectral stimulus with other wave-lengths. The simplest method would seem to be to mix a standard "white" with the spectral stimulus and to vary the proportions of the two in the mixture. However, the results obtained in this way should be compared with those accompanying other methods, such as the use of complementary wave-lengths in different proportions, or of three-stimuli combinations, such as would be required in the case of the greenish colors of the spectrum.

The experimental study of *color-blindness* is of course of perennial interest. There is still plenty of room for careful determinations of the color-mixture functions for various types of color-blind individuals, provided the conditions under which such determinations are made are specified in reproducible terms. However, it would appear that, even more important than a repetition of these conventional measurements, is the study of the general visual, and especially achromatic, visual characteristics of such color-blind individuals. As examples of the type of work needed in this field we may refer to the recent studies of Hess[179] and of Guttmann.[180] The hue scale, the saturation scale, the Weber-Fechner relation, contrast phenomena, psychological primaries, etc., should be ascertained for color-blind subjects of various types. There appears to be a good deal of uncertainty at the present time regarding the exact number of congenital forms of color-blindness, and it is to be hoped that some careful student will undertake to sift out the really characteristic types, to evaluate the evidence for and against their hereditary origin, and to determine their statistical relationships to fluctuations in the normal type. This does not mean that acquired color-blindness, resulting from retinal or brain disease or from poisoning of various types, is lacking in interest. On the contrary, the more data we have upon the effects of pathological conditions upon color vision the better will be our position to attempt an analysis of the mechanism which probably underlies the entire process. One of the

most interesting recent attempts to classify important types of color-blindness is that of Schjelderup[181] in connection with his new theory of color-vision. It is obvious that the original restriction of color-blind types to protanopes, deuteranopes and tritanopes is no longer adequate, and we must make allowances in our color theories for more types of variation than are indicated by primitive considerations concerning the visual mechanism.[182]

SECTION 16.—FORM VISION (PHASE C).

The above considerations regarding brilliance and chromatic vision may be regarded as applying to the colors which are given at any single *point* in the visual field. In other words, they apply to *elements* in the psychophysical system. The arrangements of these elements within the visual field, or in the cross section of the response at various levels, present us with the problems of visual *form*. These problems may be divided into two general classes, according as they are concerned with monocular vision only or with binocular vision.

Monocular Form.[183]—Monocular form vision appears to depend upon a very straightforward, part-to-part, relationship between the monocular visual field and the retina. To the first order of approximation, or quite accurately in the center of vision, each discriminable visual area is correlated with a separate retinal rod or cone. Outside of the center of vision, however, discrimination is not as fine as would be indicated by the number of receptors present, a fact which is apparently explained by the connection of a considerable number of peripheral receptors to single nerve conductors, whereas in the fovea each receptor has its own "private line." It would seem, therefore, that as should be expected, the ultimate physiological basis of the form element in vision is not the individual receptor, but the individual optic nerve conductor. It is furthermore clear that the constitution of the visual projection area of the cerebral cortex, in terms of unit synapses or other neurological elements, is probably of even more direct psychophysical significance, and that the pattern of excitation of these cortical components provides a sufficient basis for the pattern which appears within the visual field.

Although the investigations of Helmholtz and his contemporaries indicated that, at least in the center of vision, the threshold of acuity corresponds very exactly with the angular sizes of the retinal receptors, modern studies have indicated a considerably finer power of discrimination than this. The foveal cones subtend an angle of approximately 56 seconds of arc, but recent studies made by French[184] indicate that separations of juxtaposed lines as low as one second can be

detected. This is apparently due to a summation of influences exerted upon a considerable number of receptors, arranged in a staggered relation to one another, although French believes that the postulation of sub-receptoral discriminative mechanisms is necessary. This line of investigation is worthy of further pursuit.

Even cursory studies make it clear that the part-to-part correspondence between the monocular visual field and the retina cannot be represented by an undistorted superposition or registration of points in the two systems. This is shown, for example, in the phenomenon of the filling in of the blind spot, together with the curious displacements of objects or images seen near the margin of the blind spot, and also by the "concentric shrinkage of the visual field," which makes the psychological area corresponding to the fovea relatively greater than that of peripheral receptors. Very strange distortions of the relation between the receptor field and the psychological field appear in cases of retinitis,[185] hemanopia, hemiamblyopia[186] and other pathological conditions. In general, it would seem a very interesting problem to determine, as a part perhaps of the study of psychological visual space, the exact relationships which exist in the normal individual between the monocular field in consciousness and cross sections of the response system taken at various stages in the latter.

As a part of the study of monocular form vision, it is necessary to consider phenomena of irradiation and contrast in so far as the latter modify the contours of visual objects. In some cases these effects can be explained in terms of the sense-organ stage in the response, for example, as results of the scattering of light by various portions of the ocular media. In this case, although there is a distortion of form between the object of vision and the visual object in consciousness, the latter may faithfully represent the retinal image. In other cases the distortion must be traced to the inhibition or facilitation of neurological elements by the activities of their physiological neighbors. Although the investigation of these second-order distortions of form cannot be considered of prime scientific importance, they nevertheless provide many opportunities for the application of refined techniques of analysis,[187] and it is always possible that the results which are achieved may throw a new light upon some fundamentally important conception.

Another closely related group of questions is concerned with the so-called optical illusions,[188] which are distortions mainly of monocular forms, these distortions being seemingly dependent upon the peculiar natures of the forms themselves. One component in the form,

to which attention is directed, seems to be modified by the simultaneous presence of other components. There can be little doubt that the physiological mechanisms of optical illusions are to be found in the brain rather than in any more peripheral, afferent, stage of the response. However, the matter is now a subject of investigation as to whether these illusions are due to strictly central processes or whether they are conditioned by the manner in which the effector apparatus of the eye automatically responds to the stimulus patterns which are involved. The recent studies, reported by Wingender,[189] by a stroboscopic method suggest a possible means for settling this dispute. Among other optical illusions which have always as well as recently attracted great interest, is that of the apparent increase in size of heavenly bodies seen at the horizon as compared with their appearance at the zenith. Recent writers express the most diverse views with regard to this phenomenon, which was discussed even by the ancients.[190]

Binocular or Stereoscopic Form.[191]—The forms of visual objects in the third dimension of depth appear to depend mainly, and probably primarily, upon the relation between the patterns of excitation of the two retinas, and their corresponding nerve connections. Points or receptors upon the retinas which are similarly situated with respect to appropriate reference axes in the two eyes are called corresponding points, and the simultaneous, similar excitation of any two such points yields a fused result in consciousness. This "visual object" is localized, in the three-dimensional visual space, on a surface corresponding with physical surface or line which contains the intersection of the lines of sight of the two eyes. This surface or line is obtained theoretically by finding the locus of the intersections of direction lines from both eyes passing through corresponding points of the two retinas, and is called the *horopter*. Theoretical determinations of the shape of the horopter for various angles of convergence were made with great mathematical acumen by Helmholtz and his contemporaries,[192] and there can be little doubt at the present time of the great systematic importance of their results. The problem of the horopter, however, deserves further detailed experimental analysis, directed toward an ascertainment of the deviations of the empirical horopter from the demands of theory.

The localization, within the visual field, of the perceptions corresponding to objects of vision lying upon the horopter, would seem to depend not upon retinal but rather upon ocular, kinaesthetic or proprioceptive clues. However, experiments to test this hypothesis have thus far failed to corroborate it and Hering believed that secondary criteria of depth were the essential factors involved.[193] This is a

problem of the utmost importance which still remains unsolved. Whatever the answer may be, it is evident that clues exist which provide a system of reference, with respect to which the perceptions corresponding to objects of vision not lying upon the horopter, are localized on the basis of the degree and direction of their failure to stimulate corresponding retinal points. This *disparation* has a tendency to produce diplopia or a doubling of the visual object in consciousness. A limited amount of disparation, however, yields, instead of diplopia, a single percept or percept element having a definite location with respect to the surface which represents the horopter.

Some problems which arise in this connection are as follows: How much disparation in terms of visual angular size is required to produce a just noticeable displacement of a percept point in the depth dimension with respect to the reference plane? What is the maximal disparation which will yield a unitary perception? Is the psychophysical mechanism which translates disparation into position in the depth dimension innate or is it acquired by experience? The first two questions must evidently be answered by separate measurements taken at each point of the visual field and for a representative array of positions of the fixation point in physical space. Since it appears inevitable that the disparation threshold should depend upon the angular dimensions of the retinal receptors, it is of especial interest to study the correlations existing between monocular visual acuity and depth acuity in different portions of the field and for different individuals. A pioneer in this study was Greef, and recent researches upon this problem have been made by Howard.[194]

In general, the observation may be made that recent studies upon binocular form vision have been of a superficial character and have exhibited a regrettable ignorance of the mathematical ideas which were advanced and pursued by Helmholtz, Hering and Donders. Some recent publications, such as those of Bard, can scarcely be regarded as other than absurd in this respect. The earlier workers attacked the salient questions in a vigorous manner, but left many loose ends which should be taken up anew and woven into a coherent account.

Modern writings upon the third dimension of visual space have concerned themselves to a preponderant extent with the *secondary* or so-called psychological *factors in depth perception.* There can be no doubt whatsoever of the importance of these secondary criteria and efforts to identify and to separate them are worthy of the utmost encouragement. The parts played in depth perception by apparent size in the case of familiar objects, of atmosphere or aerial perspective, relation to the horizon, of the covering of one object by another, of

kinematic perspective accompanying movement of the head or body, etc., undoubtedly depend entirely upon empirical association between visual and kinaesthetic or tactual images. It is furthermore quite probable, as originally suggested by Bishop Berkeley and as advocated in modern times by Kaila[195] and others, that depth perception on the basis of disparation also depends, at least physiologically, upon associations established by experience.

The part played by eye movements in form vision either monocular or binocular is still a debated question. A curious but inevitable feature of visual perception is that a fixed monocular size yields a variable size in the dimensions of heighth and breadth, with variable depth, as in the case of an after-image "projected" upon surfaces at various different distances. This makes it clear that the mechanism underlying depth does not simply add a third dimension to visual experience but radically transforms the data of monocular sensations and incorporates them in a new system.

Retinal Rivalry.—Closely associated with the fusion of binocular impressions are the phenomena which ensue when qualitatively or quantitatively different stimuli are applied to corresponding retinal points. Such discrepancies of stimulation may be such as to produce either differences in brilliance or in chroma and may or may not involve differences of contour. In the case of chromatic discrepancies it is still a moot question as to whether fusion or binocular color mixture can be obtained. As it seems that different results are obtained upon this problem by various investigators it would appear profitable to attack this question in a statistical way.[196] Where rivalry, or an alternation of the sensations attributed to the two eyes individually, occurs the frequency of alternation seems to be a function of the degree of difference between the discrepant stimuli, but the mechanism underlying the alternation is still undemonstrated. The recent work of Coleman[197] shows the importance of the oxygen content of the blood for these changes and in general it would appear probable that the mechanism is central. However, investigations such as those recently made by C. N. Clark at the writer's laboratory to rule out an influence of peripheral factors should be continued. Experiments with binocularly discrepant stimuli are of great systematic importance on account of the fact that they permit certain manipulations of central processes without accompanying retinal effects. The phenomena of binocular contrast, both simultaneous and successive, the relationships surrounding "Fechner's paradox" and the interesting results obtained by Sherrington upon binocular flicker should be studied further in a quantitative way.

SECTION 17.—MOTION VISION (PHASE D).

Although motion perception is closely dependent upon form vision it appears to involve principles and mechanisms of its own.

Visual motion perceptions seem to be of two distinct types, the first depending upon a translation of an image across a succession of retinal receptors, while the second involves a pursuit of the object by the eye, which maintains approximately constant the position of the image upon the retina. The form of experience which arises in connection with these two processes, however, is substantially the same, indicating that the brain process is very flexibly attached to the pattern of retinal excitation. Holt finds that the failure of vision to blur as a result of voluntary eye movement is a consequence of central anaesthesia during this process.[198] The impression of motion which accompanies eye movement is in part referable to propioceptive impulses derived from the oculomotor mechanism, but its principal basis seems to be identical with that which underlies motion perception with a stationary eye. This consists simply in an exchange of similar excitations between adjacent elements of the retina or of the optic nerve.

Motion Thresholds.—According to the work of Aubert, the lowest velocity of retinal displacement which will yield perceptible motion is approximately one minute per second, which amounts to a passage over approximately one retinal cone in unit time. Aubert and Bourdon[199] have determined this threshold as a function of position in the visual field. A threshold for length of path can also be determined. This, according to Basler, agrees approximately with the acuity threshold. Although numerous quantitative studies have been made upon these thresholds, it would seem of interest to analyse their interrelationships in further detail; for example, to determine the speed threshold as a function of the path or *vice versa,* at different positions within the field. The interrelations of these motion perception thresholds and of acuity under various conditions, including stimulus intensity, are also worthy of further study.

The Stroboscopic Phenomenon.—It is clear that since the visual system is not, at least upon the physiological side, a continuum but is rather a mosaic of functionally isolated elements, all motion perception must have essentially the same mechanism which underlies the so-called stroboscopic illusion. A series of impressions are in all cases separately received by the retina and separately transmitted to the brain, where presumably they are integrated in such a way as to evoke the motion experience in consciousness. The stroboscopic experiment, therefore, provides us with the materials for an analysis of

the laws governing all motion perception. In this field the most systematic researches have been made by Wertheimer[200] and his pupils. The effects which are obtained involve, not only the special mechanism which specifically underlies motion perception, but also the persistence or inertia of the entire visual excitation. In addition to the persistence characteristics of the given excitations, the main factors in the stroboscopic process are as follows: the duration of successive stimuli, the duration of the interval between stimuli, the number of successive stimuli, the angular distances between homologous points in successive stimulus images, the intensity of the stimuli, their positions within the retinal field, and the sizes of the successive images. The studies of Wertheimer, Korte and others have presented us with answers to a considerable number of problems concerning the relationships obtaining between these numerous factors. However, plenty of work remains to be done in this field and moreover Wertheimer's researches have themselves opened up a host of new questions, such as those involved in the phenomena of part motion (Teilbewegung) and the "phi phenomenon" which latter has recently been studied very carefully by Dimmick. Other workers upon these problems who should be mentioned are Fischer[201] and Marbe.[202]

Although the stroboscopic phenomenon has attracted a great amount of interest over a long period of time, we are still very far from possessing a comprehensive analysis of its conditions. Because of its practical importance for motion picture production, as well as on account of its bearing upon psychophysical theory, it is worthy of renewed research attacks. A rather careful analysis of the literature in this field made several years ago by the present writer showed that data then extant were inadequate to permit secure applications to motion picture practice.

It should be recognized that motion perception which involves visual channels is usually not independent of other sensory excitations. It is very difficult to discriminate introspectively between motion experiences due to the semi-circular canal mechanism of the inner ear and those derived from ocular sources. Moreover, the nystagmic reactions of the eyes in dizziness provide a truly visual basis for motion experiences which ultimately root back into the labyrinthine sensibility. Consequently studies of visual motion should be made with a broad psychological view.

SECTION 18.—VISUAL RELATIONS ESSENTIALLY INVOLVING TIME (PHASE E).

As a purely logical matter, it might seem advisable to classify all of the facts and problems of visual psychophysiology under the four captions employed above, since practically all visual effects must be

expressed in terms of brilliance, chroma, form, or motion. However, there are certain relationships which involve some, if not all, of these factors in the same general way, so that it is in the interests of economy in thinking to consider them together. One set of relationships of this sort centers around time, while another essentially involves spatial factors as the independent variables. We shall consider briefly the former, in the present section.

Adaptation Functions.—Relatively slow changes in the chromatic or achromatic characteristics of a color, which tend to counteract the initial result of the given stimulus, are usually called processes of *adaptation.* The study of such changes indicates very clearly that they are due to alterations in the specific sensitivity of the visual system to the acting stimulus, since effects produced by one condition of stimulation carry over proportionally to any immediately succeeding stimulus. Investigation has also made it perfectly clear that the visual system involves two distinct mechanisms of adaptation which are attached respectively to the rods and to the cones.

The processes of rod adaptation have been very thoroughly studied by such earlier investigators as von Kries,[203] Nagel, Piper[204] and such later ones as Nutting,[205] Blanchard[206] and Cobb.[207] Our knowledge of the laws and conditions of rod adaptation may be regarded as being in a fairly satisfactory state. The greatest uncertainty in this field would appear to relate to the degree to which the rod processes are involved in ordinary daylight vision. Does their adaptation to intense stimuli reduce their sensitivity to zero or is there a slight residual participation of the rods in vision even at the highest intensities? Another aspect of dark adaptation which has not been thoroughly investigated is that of the action of stimuli of restricted area. Probably on account of the inferior form vision of the periphery, this problem of scotopic negative after-images has been neglected. The influence of adaptation processes of one eye upon those of the other is also a question requiring further investigation, as is that of the exact physiological mechanism which underlies or controls the process in a single eye. Existing evidence indicates that rod adaptation is under the control of efferent impulses.

Cone Adaptation.—There can be no doubt whatsoever that the cones, or their attached nervous mechanisms, undergo processes of adaptation analogous to those which occur in the rods. The times required for the cone adaptation to reach equilibrium are, however, very much less than those needed for a similar state to be attained in rod adaptation (one to two minutes as compared with forty-five minutes). As shown by the writer, the curve of cone adaptation is an asymptotic one which, contrary to the implications of the Hering

theory, does not as a rule bring the specific cone sensitivity which is involved to a zero value.[208] Von Kries employs the word *Umstimmung* to designate cone adaptation in contradistinction to rod adaptation, and the present writer has suggested the term *minuthesis* for this purpose, to replace the objectionable word "fatigue."

Rod adaptation is uni-dimensional since it can be expressed in terms of brilliance alone. The corresponding cone process, however, is at least bi- and in all probability tri-dimensional in its possibilities, since there may be minuthesis not only for brilliance but for the saturation of any given hue. Prior to the investigations of the present writer, the most accurate work upon the laws of cone adaptation was that of von Kries[209] who determined the adaptation curves for stimuli of various intensities and wave-length composition. Von Kries' work substantiates the so-called coefficient law, according to which the effect produced upon both brilliance and chromatic matches can be expressed by the introduction of a coefficient representing the degree of minuthesis. This law requires further careful study. Of particular interest in this connection is the degree to which the sensitivity of the cones, as represented either by chromatic or achromatic response, is reduced by equilibrium adaptation to stimuli of various intensities or wave-length composition. Extant results make it clear that the higher the intensity the greater the corresponding reduction in sensitivity but the exact law connecting these two variables has apparently not been ascertained for cone vision unmixed with rod process.

A problem which is of great theoretical interest in connection with cone adaptation is that of the degree of correlation which exists between minuthesis for brilliance and for specific chromatic attributes. The Young-Helmholtz theory, as interpreted by Abney, implies that brilliance minuthesis accompanying a stimulus of one wave-length should not carry over by a fixed coefficient to a stimulus of quite a different wave-length. The Hering theory on the other hand, is consistent with at least an approximate independence of the brilliance adaptation effect and the chromatic aspects of the process. The investigations of Abney himself favor the Young-Helmholtz conception, but work being carried out in the writer's laboratory is more favorable to the implications of the Hering theory.[210] In connection with this problem it would be of great interest to make a comparative determination of the temporal laws both of "fatigue" and "recovery" for brilliance and the chromatic attributes respectively.

Growth and Decay Functions.—Another group of temporal psychophysical relationships are those which underlie the so-called per-

sistence of vision. Probably more work has been done upon this particular problem, relative to its importance, than upon any other in visual science. Our knowledge of the quantitative laws governing flicker, both chromatic and achromatic has been brought to a very high degree of completeness by the researches of a long series of investigators culminating in Ives, whose mathematical theory of the flicker photometer[211] marks a high point in visual science. The determinations, by numerous methods, of the curves of rise for various colors have recently been reviewed and to a large extent repeated by Bills[211a] whose work may be regarded as saying the last word upon this subject. The investigations of Swan,[212] Charpentier,[213] McDougall [214] and others have shown that the rate of rise is proportional to the stimulus intensity for any given wave-length and that the "action time" or time required to reach the maximum is approximately inversely proportional to the logarithm of the intensity (Exner,[215] Martius[216] and McDougall). The measurements made by Broca and Sulzer[217] showed a clear difference in the rates of rise for different hues. Bills finds that for equal brilliance the yellow (580 $m\mu$) exhibits the greatest speed while the blue (463 $m\mu$) tends to be the slowest, but the results of this investigator are somewhat equivocal, so that this very interesting problem merits further experimental study with a considerable number of observers.

Studies of the rates of rise of visual sensations have as a rule related to the brilliance attributes even when chromatic factors were present. It is quite conceivable that the chroma of a color should rise or decay at a different rate from its brilliance, and investigations should be undertaken to determine these functions for the chromatic attributes, without reference to the accompanying brilliance. Work thus far recorded upon the curves of rise and fall of the chromatic attributes consists mainly in measurements (by Berliner,[218] Brückner and Kirsch,[219]) on the time of stimulation required just to render the chromatic attributes perceptible. There is plenty of room for important researches in this field. The curve of decay, either for brilliance or for chroma, has been studied much less intensively than has that of growth. Fick[220] found the de-excitation function to be representable by a saturation curve similar in form to that of excitation, inverted. Further quantitative work upon the former curve would not be out of place. It would be of particular interest to determine the decay function for a series of durations of the stimulus, thus linking it up with the minuthetic effect of the latter. The study of the decay curve is in general complicated by both positive and negative after-image phenomena.

Flicker.—Closely associated with the problem of the decay curve is that of *flicker*, in which a second stimulus is applied shortly after the removal of the primary one, this process being repeated. The critical flicker frequency or the speed of alternation of light and dark intervals which is just high enough to eliminate flicker has been shown by numerous investigations beginning with that of Porter[221] to be proportional to a logarithmic function of the intensity, the constants of this function changing abruptly in an intensity region corresponding to the transition from cone to rod vision. The constants also vary, according to Ives,[222] for different wave-lengths of the stimulus in photopic vision. A careful redetermination of these constants or laws for different spectral stimuli is much to be desired. The critical flicker frequency has been found to depend upon the following additional factors: (1) the intensity difference between successive stimuli, (2) the duration difference between stimuli, (3) the number of intervals of different intensity in a single period, (4) contrast with areas outside the test field, (5) size of the test area, (6) minuthesis, (7) rod adaptation, (8) position in the visual field, (9) pressure on the eyeball. Although the studies on the phenomena of flicker and of fusion have been numerous, there is still indefinitely great scope for further researches upon their conditions. Fewer researches have been done upon *chromatic* flicker, in the absence of flicker due to brilliance variation. The condition for a match, in the flicker photometer, yields equality of brilliance with chromatic differences still effective, and a frequency of alternation of the two stimuli can be found at which the flicker due to these chromatic disparities just disappears. This "flicker photometer frequency" follows laws quite independent of those for brilliance flicker. As shown by the present writer,[223] it is in general a power function of the stimulus intensity, the constants of the function varying with the wave-length composition of the stimulus. Relatively little has yet been done in the quantitative study of purely chromatic flicker, although the theory of such flicker in relation to brilliance flicker has been very clearly discussed by Ives.[224] It would appear that the first attack upon this general problem should be a complete study of chromatic flicker laws, involving the alternation of all possible chromatic stimuli with a gray-producing stimulus of equal brilliance. It is a well recognized fact that the utility of the flicker photometer depends upon the elimination of chromatic flicker through fusion at frequencies much lower than those required to obliterate brilliance flicker.

Fusion.—When rates of alternation of different stimuli, whether chromatic or achromatic are sufficiently high to eliminate flicker, the

fused color which results is the same as would be evoked by a non-intermittent mixture of the same stimulus energies. This is expressed for brilliance by the well-known Talbot-Plateau law, and for chromatically diverse stimuli by the results of myriads of color experiments made with rotating disks. The work of Kleiner,[225] Ferry,[226] Wiedemann,[227] Hyde[228] and others shows that the Talbot-Plateau law is absolutely valid over a very wide range of conditions, and it seems that these fusion principles can now be accepted without question except for borderline conditions.

Positive After-Effects.—When a stimulus is cut off soon after the maximum excitation is reached, or before, a complicated series of oscillatory changes supervenes upon the immediate decay of the sensation. The latter decay carries the excitation down to a point considerably below that corresponding with the normal idio-retinal light. It then rises again with equal rapidity, falls once more below normal, rises again more slowly and then sinks the third time to return finally to the normal level after a period of about 10 seconds. These oscillations are best seen by the use of a moving stimulus, in which case the different phases are spread out adjacently in space behind the moving light. Very careful studies of these after effects have been made by Hamaker,[229] Hess,[230] von Kries,[231] Boscha,[232] and others. The secondary image has been shown by von Kries to depend upon dark adaptation and to be absent in the fovea, so that it may be taken to represent the delayed response of the rods, the primary image being due to the cones. The tertiary image appears to be a positive after-effect associated with the cone system. A great deal of room still remains for quantitative study of these complex phenomena under various conditions of adaptation, stimulus composition and position within the visual field. Recent experiments by Ives[233] suggest that an analysis of these phenomena may throw great light upon our understanding of the visual mechanism. In general, it may be regarded as very important to effect a definite separation of the rod from the cone reactions, both with reference to these after-effects and to the growth and decay characteristics of primary excitations.*

When the stimulus is not cut off quickly upon attainment of maximal excitation, oscillations having a relatively high frequency ensue. These are demonstrated with a moving stimulus in the form of Charpentier's bands. The quantitative studies of McDougall[234] and others upon the frequency of oscillation represented by the bands

* The recent, very significant researches of Fröhlich (*Zeits. f. Sinnesphysiol.*, 1921, 52, 60–103; 53, 79–121) indicate that the essential mechanism of the periodic after-images is central in localization, and that there is no specific dependence of any of the images upon rod or cone function, respectively.

should be continued under improved conditions since the oscillations in question are suggestive of the pulsatory character of the nerve impulse, and a determination of their dependency upon intensity and wave-length may throw great light upon our understanding of visual response.

Form and Motion After-Effects.—The temporal relationships of form vision are, for the most part, bound up with those of brilliance and chromatic vision, ordinary "after-images," either positive or negative being temporal phases of brilliance or chroma having definite forms, conditioned by the shape and localization within the retinal field of the primary stimulus. It should be noted, however, that form itself is, in some cases at least, independently determined by time relationships since initial, terminal, or intermediate phases of an excitation may yield different forms for a stimulus which is itself of invariable pattern. The mechanism of these form changes, as for example those which appear in the various after-images of a moving light spot, usually involve the interrelationships of various differently localized intensity changes.

Certain temporal relationships of motion vision are naturally considered in the study of the stroboscopic and related phenomena since motion itself intrinsically involves time. However, the negative motion after-image which has been studied by Helmholtz,[285] Dvorak[286] and others, makes the subjective motion experience in vision an extrinsic as well as an intrinsic function of the time. Careful quantitative studies on these motion after-effects which, like those of brilliance and chroma can be confined to small definitely delimited visual areas, would undoubtedly pave the way to an understanding of certain central mechanisms in vision which are now obscure.

In general, we may look upon the special temporal relationships of the factors in vision as a very hopeful means by which to separate or to correlate these factors and thus to obtain aid in our attempt to analyze and to reconstruct the total psychophysical mechanism.

SECTION 19.—VISUAL RELATIONS ESSENTIALLY INVOLVING PATTERN OR POSITION (PHASE F).

Vision with respect to brilliance, chroma, form, or motion is dependent upon absolute position within the visual or retinal field and upon relative position with respect to other concomitant excitations within these fields. These dependencies may be classified, accordingly, as *field functions* and *pattern functions* respectively, the former involving the problem of "retinal zones," etc., while the latter embrace contrast and related phenomena.

Field Dependencies of Brilliance and Chroma.—The anatomically determined distributions of the rods and the cones, respectively, over the retina imply the dependency of both brilliance and chroma vision upon position within the field. This involves not only the relative numbers of rods and cones in different meridians or zones, but also the densities of these two respective receptors. The laws connecting brilliance with position in the field depend radically upon the state of rod adaptation. A similar dependency exists for the relations of brilliance and wave-length, as well as of brilliance and purity. Extant data upon these relationships indicate their conformity with what should be expected from the anatomical distribution of the two types of receptors and the established characteristics of their respective psychophysical responses. With photopic adaptation, intensity thresholds increase from center to periphery while with scotopic adaptation the reverse change is found. The visibility function for peripheral photopic vision appears to be identical with that of central vision (von Kries[237]) while that of peripheral scotopic response represents the characteristic curve for the rods. Further studies upon peripheral visibility especially with scotopic or cone vision are desirable.

On account of the clinical and theoretical importance of the relationships involved, the study of the dependency of chromatic vision upon position in the field has received a very considerable amount of attention. Unfortunately, however, completely satisfactory conclusions appear as yet not to have been reached with regard to this question. That chromatic vision decreases from the center towards the periphery is admitted by all investigators, and it is also generally conceded that the red and green values fall off more rapidly than the blue and yellow. Hering,[238] Hess,[239] and their school have maintained that the peripheral limits for red and green and for yellow and blue, respectively, were in exact coincidence when colors of equal brilliance and saturation were employed. This contention was substantiated by Baird.[240] However, the recent work of Ferree and Rand[241] has educed evidence in opposition to this notion. These latter investigators find no exact correspondence of the retinal zones for different colors and they assert that all spectral colors with the exception of green can be perceived as chromatic to the extreme periphery provided sufficient intensity is provided. This problem is still a very live one, requiring further study with very careful attention not only to conditions but to definitions. In the latter connection it should be noted that equality of saturation cannot be understood in a physical sense but must rest upon a psychological or at least

upon a physiological criterion. The standardization of test objects for clinical campimetry has recently attracted considerable attention [242] and merits further efforts.

Field Dependencies of Form and Motion.—The dependency of visual acuity [243] upon position in the field has provided the problems for many researches. There is further room, however, for study of this relationship under various conditions of (1) rod and cone adaptation and (2) pupillary aperture and degree of accommodation. An intercomparison of the results of such studies should enable us to separate the factors which are due to the refractive apparatus from those attributable to the neurological mechanism. Exactly similar considerations apply to the various distortions of form which occur in various stages of peripheral as compared with central vision. The dependencies of form within the third or depth dimension, upon position within the monocular field may also be noted as a relatively neglected topic.

It is a well-known fact that the peripheral visual field possesses relatively great sensibility to motion, all stimulus changes tending to be represented in consciousness as movements. Aubert,[244] and Bourdon [245] have determined the speed threshold for motion perception at various peripheral angles. Czermak [246] found that the apparent velocity of objects in the periphery is less than in the center. We may ask what characteristic of the organization of peripherally connected neurones maintains their ability to detect motion at so high a level when their form sensibility has been so radically reduced. It is to be noted that the refractive processes of the eye are also involved in these relationships.

Contrast Relationships for Brilliance and Chroma.—Contrast involves a reciprocal alteration of adjacent colors or excitations in such directions as to increase the difference which would have existed between them without contrast. In general the degree of the contrast effect is greater, the greater the primary difference and the closer the contiguity. Absolute intensity or purity levels, as well as position and size in the visual field, are also essentially involved. Hess and Pretori [247] find the increase of the brilliance difference between two contrasting colors due to contrast, to be proportional to their primary difference, but Lehmann [248] believes a more complicated formula to be necessary. Further investigation of the quantitative laws of achromatic contrast would not be out of place. Quantitative studies of chromatic contrast have been made by Kirschmann [249] and by Pretori and Sachs.[250] Kirschmann refutes the view

of Helmholtz, that chromatic contrast is the greatest for colors of low saturation. The former investigator found that the contrast effect is proportional to the logarithm of the saturation, a similar relationship holding between contrast and the magnitude of the contrast-inducing area. Although the general law of chromatic contrast appears to be that the two contrasting colors are altered mutually in the direction of a complementary relationship, it appears (Hering) that contrast hues are not always strictly complementary. A study of the conditions underlying deviations from the general rule in this respect would be of interest.

In general, it may be noted that although the phenomena of contrast have been studied qualitatively for centuries, the quantitative examination of these effects has been very meager. Methods for quantitative investigations are not hard to find, it being possible to establish equations between color areas which are subject to contrast, and other areas which are not thus affected, using either monocular or binocular vision. Another method is to neutralize the contrast effects in the area affected, by the addition or subtraction of appropriate stimulus factors. Pretori and Sachs, as well as Hess,[251] find by this method that, to neutralize a chromatic contrast effect by the addition of a complementary stimulus to the affected field, a quantity of such complementary is required proportional to the saturation of the contrast-inducing color.

The higher psychological or cortical relationships of contrast, especially of chromatic contrast, are of the utmost interest. The reduction of contrast which results from differences in texture between the contrasting images caused Helmholtz [252] to regard all contrast effects as purely psychological. Although Helmholtz's belief in this regard is almost certainly erroneous, there is no doubt that cortical factors can either inhibit or facilitate the contrast process. The practically instantaneous character of the contrast effect indicates that it has a conductional or a central mechanism rather than a receptoral one. The "color constancy of visual objects," which was explained by Hering mainly upon the basis of contrast, almost certainly involves special cortical or psychological mechanisms although contrast is undoubtedly one of the principles upon which it rests. The work of Katz,[253] Jaensch [254] and their pupils is throwing much light upon these problems.

The dependency of contrast effects upon the areas and shapes of the stimuli and the distribution of the effects within the areas concerned have been studied by numerous investigators. The distinc-

tions between border contrast, surface contrast and internal contrast [255] need to be considered carefully in relation to (1) the physiological theory of the effects and (2) the probable function of contrast in compensating for the smearing of light by the ocular media, and for the variations in intensity and wave-length composition of the radiation by which objects are normally seen.

Recent studies by Cobb,[256] Schjelderup,[257] Dittmers [258] and others have revealed a very important dependency of brilliance discrimination upon brilliance contrast. Similar experiments should be made upon chromatic contrast.

In all quantitative researches upon simultaneous contrast it is highly important to eliminate effects of adaptation, either general or local, since these may either augment or oppose the true contrast effects. It appears on the whole that the designation of negative visual after-effects as "successive contrast" is misleading, since the mechanisms which are involved in this process are in all probability quite different from those which are concerned in simultaneous contrast. However, in attempting to work out the relationships between contrast and other visual processes, it may prove valuable to combine, into contrast patterns, colors due to local minuthesis and others due to stimulus differentiation. We find in fact that contrast effects are very clearly manifested in after-images.

The effects of brilliance contrast are apparently not confined to brilliance but extend to the chromatic aspects of sensation, a color which is subject to the contrast influence of a very brilliant outlying field being greatly desaturated, while upon a dark background a similar effect is produced. Equality of brilliance between the two areas apparently provides the condition for maximal saturation. Brown and related dark colors, including black itself, are evoked only under contrast conditions. It is claimed by Hering that conversely, brilliance values are affected by achromatic contrast. All of these topics require further quantitative investigation.

Of particular interest are observations on contrast in color-blind individuals where, as demonstrated by Guttmann [259] and others, contrast chromas can be evoked in the conscious absence of the contrast inducing color. Similar effects have been found in peripheral vision, for certain subjects, by Ferree and Rand and indicate that the mechanism of contrast, at least in these instances, is retinal rather than central.

Areal Functions.—A considerable amount of excellent quantitative work has been done by Riccò, Charpentier, Loeser and especially

by Piéron, on the influence of the size of the retinal stimulus upon the brilliance threshold. The relationships between intensity and area at the threshold, as already indicated in our discussion of brilliance vision, are very intimate and of great theoretical importance, because of their bearing upon the minimal energy required for vision and upon the laws of interaction of adjacent visual elements. Riccò found that, in the fovea up to a diameter of about fifty minutes, the energy required for threshold excitation is the same for all areas, the product of the intensity and the area being constant. These results were confirmed by Charpentier and Loeser. For areas larger than fifty minutes in diameter, the total energy required for threshold excitation increases with the area but does not become proportional to the latter until a diameter of four degrees (Abney) is reached. According to Piper,[261] Loeser, Henius [262] and Fujita,[263] the product of the threshold intensity and the square root of the area is constant for areas lying between one and ten degrees, and with dark adaptation, this relationship being upset by light adaptation. Piéron [264] finds that in peripheral vision, for angles up to about thirty-three minutes, the product of intensity and area at the threshold tends to be constant for the cones, while for the rods the product of intensity and field diameter shows constancy. The laws of areal summation for the foveal cones are similar to those for the peripheral rods, indicating that these laws depend upon the sizes and distributions of the receptors, rather than upon their specific physiological characteristics. Piéron has furthermore studied these factors of intensity and area in combination with that of time. It is to be hoped that he will continue his work along these lines.

Donders,[265] Charpentier [266] and others have shown that with small areas and low intensities, a potentially chromatic stimulus may yield an achromatic color, and that if the area is increased the chroma may appear without augmentation of the intensity. This is true even of foveal stimulation. It is evidently possible to work out the relations between area and intensity with respect to chroma, independently of brilliance, and this relationship will also clearly involve the purity and the wave-lengths of the stimulus in question. The quantitative investigation of these chromatic relationships is of particular interest on account of the theoretical question as to whether more than one retinal receptor is required for complete color vision.

Closely associated with these problems is that of the dependency of apparent size upon intensity when the size of the stimulus is kept constant. This relationship has been studied by Asher [267] and by Abney.[268]

Section 20. The Explanation of Visual Psychophysical Correlations.

The multitudinous, visual, psychophysical relationships above discussed consist, in nearly all instances, of complex associations between the psychological factors of brilliance, hue, saturation, depth, motion, and constellations of these factors in space or time, on the one hand; and the physical factors of intensity, wave-length, purity, position and shape of the image on the retina, time of action (or after action) of the stimulus, on the other hand. In certain instances, as in the case of scotopic adaptation, we can with considerable surety restate the psychophysical relationships in terms of receptoral conditions, but as a rule we find ourselves lacking in any certain clue as to the nature of the mechanisms which link the stimulus characteristics psychophysically with those of consciousness. Nevertheless, we must regard an accurate knowledge of such mechanisms, underlying all of the indirect psychophysical relationships which may be considered, as the ultimate goal of our researches. Consequently, in all such investigations it is advisable to have in mind some definite hypothesis regarding the mechanism of the particular phenomena which we have in hand, and so to shape our experiments as to make them a test for the hypothesis in question. In this way we shall advance as rapidly as is possible in our conception of the total visual apparatus. It is highly desirable to work in this manner, not only because a knowledge of the actual physiological and psychophysical details is a legitimate goal of research, but because the possible interrelationships between the psychological factors, on the one hand, and the physical and physiological ones, on the other hand, are practically infinite in number and complexity. Without the use of hypotheses we might continue to study these manifold relationships without attaining any synthesis or any ultimate understanding of the facts. As we have seen in our preliminary discussion, it is the function of theories of vision to fill in the gaps between the facts in a systematizing way.

Clearly, a very important aspect of our theoretical endeavors in visual science will be the partition of psychophysical functions among the several stages of visual response. We shall assign certain effects, such as scotopic and possibly photopic adaptation, to the receptors. Other effects, such as Charpentier's bands may be assigned to the afferent conduction, while still others, like motion perception, will belong to the cortex. However, in partitioning effects in this way we must always carefully bear in mind the serial relationship which exists between the successive stages of the response, and we must also con-

sider the possibility that the same or very similar effects may be initiated in more than one response stage.

In some instances, we are actually able to establish empirically the relationships obtaining between visual consciousness and stages in the response other than the stimulus. This is particularly true with respect to the central process itself. The disturbances of vision which accompany lesions in the occipital lobe of the cerebrum demonstrate clearly the fact that the totality of the visual consciousness depends psychophysically upon the brain process; so that relations, such as those studied in the majority of laboratory experiments, between consciousness and the stimulus must be explained in terms of the physiological mechanism of the response, leading up to the focal region in the cortex, as well as by the direct psychophysical relation which exists between consciousness and the cortical activity in question.

SECTION 21.—CONCLUSION.

We have now passed over, in cursory review, the general characteristics and the special fields of investigation in visual science. Not the slightest pretense is made that this review has been adequate either to the established facts or to the outstanding problems. It is patently impossible to compress within the limits of a small monograph what an encyclopedia could scarcely contain. Limited as is the domain of visual investigation as compared with the totality of science, within itself it presents an aspect of staggering complexity. Any one of the topics which we have dismissed with a sentence could readily be expanded to the dimensions of the entire monograph. The function of the monongraph will be fulfilled, however, if it succeeds in making clear the general concepts of the science, and in conveying a generally truthful impression of actual achievements and failures in their applications.

Psychophysical optics has proved itself in the past to be a very fascinating field of research. Unfortunately, fascination alone does not guarantee scientific results. Still, if we must recognize that many intellectually incapable individuals have written millions of words upon this subject to no avail, we must also acknowledge that it has attracted the fruitful attention of many master-minds in science, of Newton, of Müller, of Maxwell, of Helmholtz, or Hering, of Rayleigh and many others. At the present time many extremely capable investigators are working upon visual problems, yet there is too much of the modern, as well as of the older, work which is dilettante, and scientifically valueless. There is evident in a large fraction of current

literature dealing with vision a failure to recognize the complexity of the conditions which are inevitably involved, and a consequent absence of that careful specification of all circumstances surrounding experimentation which is needed to render the results of permanent value. Moreover, English-speaking investigators appear to have a profound contempt for existing literature even when it is in their own language. Nearly every year, some classical content of Helmholtz's "Physiological Optics" is rediscovered and published. The proposal of the Optical Society of America to translate Helmholtz's great work into English will, if brought to a successful conclusion, make such redundancies inexcusable.

It is sincerely to be hoped that this monograph, as a portion of the work of the committee appointed by the Research Council to consider the status of physiological optics, will serve as a stimulus to renewed and refined studies upon vision. What we need are fewer papers and better ones. Just as it is impossible to overestimate the practical importance of vision, so also it is difficult to overrate the theoretical significance of psychophysiological optics, as a contribution to our study of mind in its relation to matter. In vision, to a degree which is nowhere else exemplified, we find the mental and the physical associated in clear and measurable ways. Let us, then, attack these classical and these modern problems of vision with renewed vigor and intelligence, so that the light of knowledge may penetrate the darkest depths of the very process upon which our knowledge of light—and so of nearly all of the world outside us—itself depends.

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